Dust emission by off-road driving: Experiments on 17 arid soil types, Nevada, USA

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ABSTRACT

Field experiments were conducted in Nellis Dunes Recreational Area (Clark County, Nevada, USA) to investigate emission of dust produced by off-road driving. Experiments were carried out with three types of vehicles: 4-wheelers (quads), dirt bikes (motorcycles) and dune buggies, on 17 soil types characteristic for a desert environment. Tests were done at various driving speeds, and emissions were measured for a large number of grain size fractions. This paper reports the results for two size fractions of emissions: PM10 (particles <10 μm) and PM60 (particles <60 μm). The latter was considered in this study to be sufficiently representative of the total suspendable fraction (TSP). Off-road driving was found to be a significant source of dust. However, the amounts varied greatly with the type of soil and the characteristics of the top layer. Models predicting emission of dust by off-road driving should thus consider a number of soil parameters and not just one key parameter. Vehicle type and driving speed are additional parameters that affect emission. In general, 4-wheelers produce more dust than dune buggies, and dune buggies, more than dirt bikes. Higher speeds also result in higher emissions. Dust emitted by off-road driving is less coarse than the parent sediment on the road surface. Off-road driving thus results in a progressive coarsening of the top layer. Exceptions to this are silty surfaces with no, or almost no, vegetation. For such surfaces no substantial differences were observed between the grain size distribution of road dust and emitted dust. Typical emission values for off-road driving on dry desert soils are: for sandy areas, 30–40 g km^{-1} (PM10) and 150–250 g km^{-1} (TSP); for silty areas, 100–200 g km^{-1} (PM10) and 600–2000 g km^{-1} (TSP); for drainages, 30–40 g km^{-1} (PM10) and 100–400 g km^{-1} (TSP); and for mixed terrain, 60–100 g km^{-1} (PM10) and 300–800 g km^{-1} (TSP). These values are for the types of vehicles tested in this study and do not refer to cars or trucks, which produce significantly more dust.

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1. Introduction

The environmental impacts of dust emission, dust transport and dust deposition have become a major concern since the early 1990s. Atmospheric dust affects human health (Griffin et al., 2001; Smith and Lee, 2003; Griffin et al., 2007; Meng and Lu, 2007) and is a source of environmental pollution (Schulz, 1992; Wilkening et al., 2000; Pelig-Ba et al., 2001; Ozer et al., 2007); it affects the fertility of soils, especially in arid and semi-arid regions (Algharaibeh, 2000; Agbenin, 2001; Reynolds et al., 2001); it plays a crucial role in the functioning of ecosystems (McTainsh and Strong, 2007), both on the continents (Sterk et al., 1996; Herut and Krom, 1996; Mikkelsen and Langohr, 1998) and in the oceans (Duce and Tindale, 1991; Baker et al., 2003; Meskhidze et al., 2005; Chase et al., 2006; Cassar et al., 2007); and it affects human activities, including economy, politics and society issues (Riksen, 2004). Although there are multiple processes involved

in producing and controlling dust emissions, these processes need to be considered at different scales:

- On the global scale (including the continental scale) wind erosion is the major source of dust. The huge amounts of dust emitted in Africa, and its transport to the west (Atlantic Ocean, Caribbean, South America) and north and northeast (Europe, Middle East) have been well documented over the last 40 years (Roda et al., 1993; Prospero, 1999; Eglinton et al., 2002; Chen and Siefert, 2004; Meloni et al., 2004; Antoine and Nobileau, 2006; Gobbi et al., 2007). In East Asia, the major sources of dust (China, Mongolia, Pakistan) and the transport trajectories to the east (Korea, Japan, western Pacific) have been described in detail (Shaw, 1980; Middleton, 1991; Zhang et al., 1993; Zhou et al., 1996; Sun et al., 2004; Takemi and Seino, 2005). Also, emission, transport and deposition of dust have been described in the Middle East (Middleton, 1986; Ilaiwi and El Asskar, 1998; Ganor and Foner, 2001; Goudie, 2002), Australia (Hesse, 1994; Squires, 2002; Marx et al., 2005; McTainsh et al., 2005) and in the western USA (Gillette et al., 1978; Gill and Cahill, 1992; Marcus and Brazel, 1992; Gill et al., 2000; Reynolds et al., 2007).
- On the regional scale, dust is emitted by wind erosion but also by human activities, especially (but not exclusively) agricultural

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activity. Tillage has been shown to be a significant source of dust as it is able to emit higher amounts of dust than wind erosion alone (Goossens et al., 2001). A long history of research focusing on tillage and dust emission exists for the USA (e.g., Matsumura et al., 1992; Ashbaugh et al., 1996; Clausnitzer and Singer, 1996; Baker et al., 2005). In Europe, the topic has been studied more recently (Goossens et al., 2001; Funk and Reuter, 2004; Goossens, 2004). The role of tillage as a dust production mechanism has also been studied in China (Du et al., 2005).

- On the local scale, wind erosion and agricultural activity remain the major sources of dust but other mechanisms also contribute to the dust load. One of these is vehicle driving, either on paved or unpaved roads. In the literature this type of emission has not yet received the attention it deserves, although studies exist for paved (Venkatram, 1999; Venkatram et al., 1999; Etyemezian et al., 2003a; Kuhns et al., 2003) and unpaved roads (Pinnick et al., 1985; Gillies et al., 1999; Moosmüller et al., 1998; Etyemezian et al., 2003b; Kuhns et al., 2003; Gillies et al., 2005).

Off-road driving can be a significant source of dust. A remarkable example is the Nellis Dunes Recreational Area near Las Vegas, Nevada, USA. This 37 km^2 large area is managed by the Bureau of Land Management (BLM) and is the sole area in southern Nevada that is freely and legally accessible to the public for off-road driving. Over 285 000 people visit the area annually (BLM, 2004) to drive their off-road vehicles in the dunes, washes, desert pavements, rock-covered hills and moon-like landscapes that characterize this part of the Mojave Desert. More than forty years of off-road driving have resulted in the creation of thousands of road tracks in the desert floor, with a total length of several hundreds of km. Apart from dust emitted by vehicles, these tracks, where the natural surface crust has been destroyed, serve as a significant source of dust during episodes of strong winds. All this has culminated in a continuous emission of dust in the area, by both natural and human activity.

Nellis Dunes Recreational Area is a very complex area. The original topography was already complicated as it is composed of an amalgam of small and medium-sized hills, plateaus, ridges and depressions, but 40 years of off-road driving have made it even more complex due to the numerous additional incisions that have been created along the tracks. Also, the area is characterized by a very large number of surface types. An ongoing study identified 17 different types of surfaces, developed on loose dune sand, compacted sand, loose silt, compacted and/or aggregated silt, rock-covered sands and silts, mixtures of sand, silt and clay, exposed petrocalcic horizons, gravelly substrata and bedrock. All these surfaces react differently when exposed to off-road driving and wind erosion. Nellis Dunes Recreational Area is thus an ideal place to study emission by off-road driving, and it also clearly illustrates the importance of geomorphological and pedological parameters in this matter.

Most studies on unpaved road emissions focus on one, or only a limited selection of soil (or surface) types. This study investigates 17 surface types, typical for North-American deserts and other deserts worldwide. Three types of vehicles were tested: dirt bikes (motorcycles), 4-wheelers (quads) and dune buggies. Other vehicles such as cars and trucks were not examined, but the vehicles tested represent more than 99% of all vehicles driven in the Nellis Dunes area.

The aim of the study was to quantify the emissions for each type of vehicle, for various driving speeds, over all 17 surface types, and for various grain size fractions. In this paper the results are presented for PM10 (particles <10 μm) and PM60 (particles <60 μm), the latter of which was considered sufficiently representative for TSP (Total
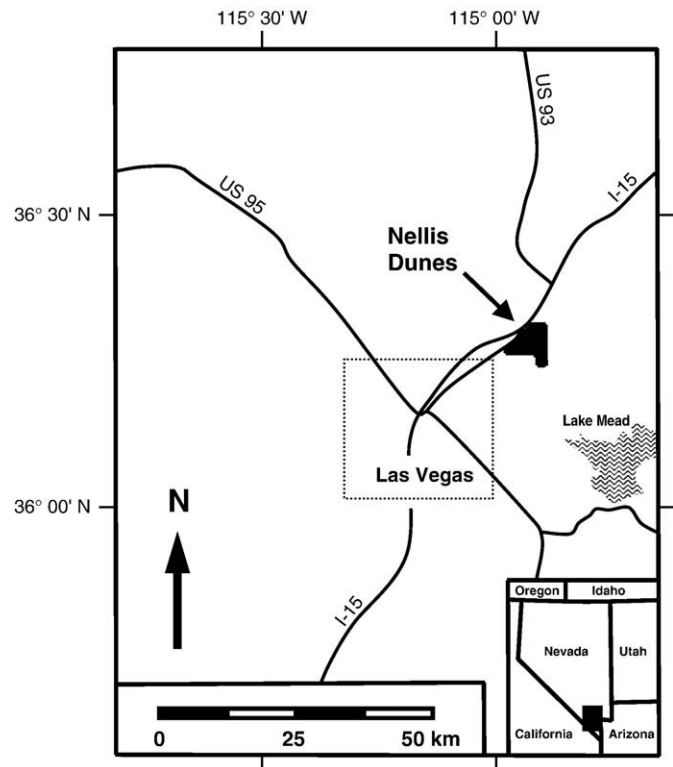

Fig. 1. Location of Nellis Dunes Recreational Area, southern Nevada, USA.

Suspendable Particles). Data on additional grain size fractions (up to 100 μm) were collected, but these will be reported in a future publication. Apart from the measured emissions, the study also examines scenarios (typical runs through the area) to get a realistic idea of the amounts of dust produced during off-road driving. Four scenarios were calculated: typical runs through a sandy area, a silty area, through drainages, and through mixed terrain. Finally, the effect on the grain size of the topsoil from off-road driving is investigated because roads are an important source of dust during episodes of strong winds.
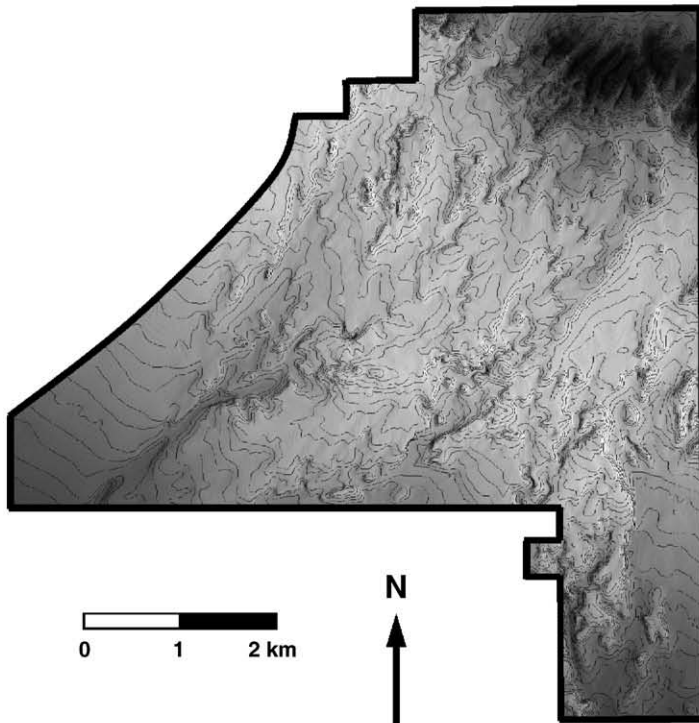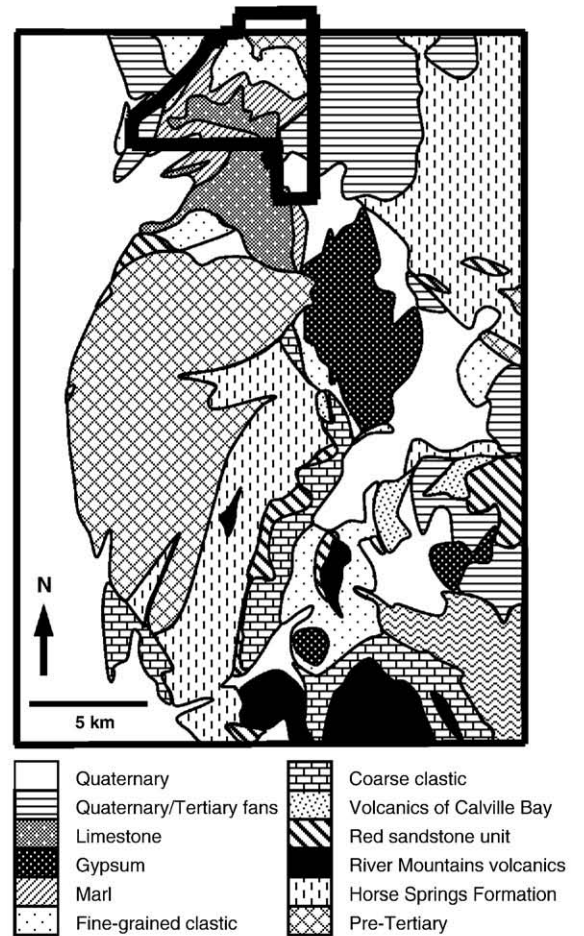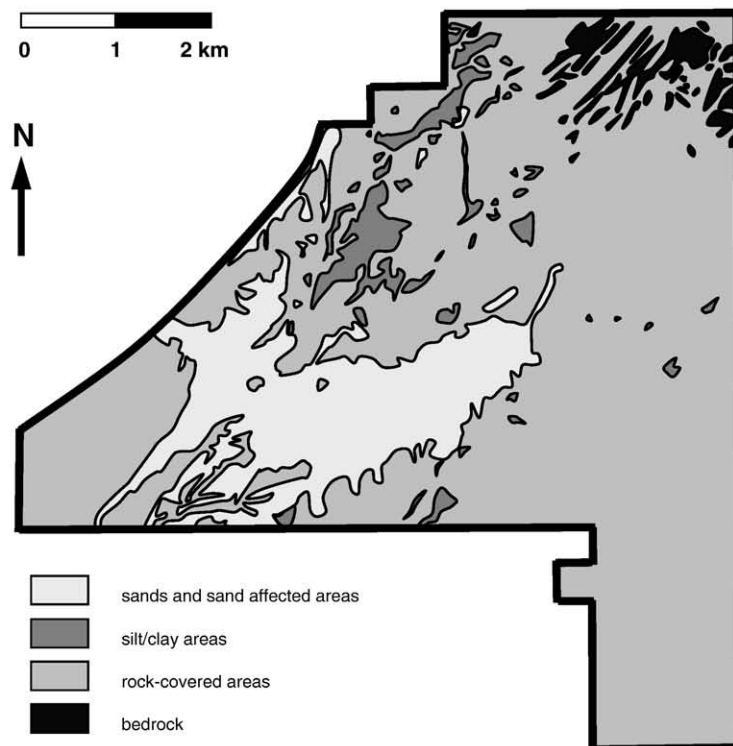
2. The experimental area

2.1. Situation

Nellis Dunes Recreational Area is located about 8 km from the northeastern margin of the city of Las Vegas, Clark County, Nevada, USA. It has a more or less triangular shape with N–S, W–E and SW–NE sides of 8.0, 7.8 and 9.0 km respectively, and a small additional rectangle 2.4 km × 1.6 km in the SE (Fig. 1). It encompasses an area of approximately 37 km^2.

2.2. Topography

The Las Vegas Valley is located in the Great Basin region of the Basin and Range physiographic province of the USA. It is an intermountain valley, surrounded by generally N–S-trending mountain ranges between 450 and 2100 m above the valley floor in the N and E, and up to 3000 m above the valley floor in the west. Nellis Dunes Recreational Area is located on the eastern side of the valley, in between the Sheep Range (to the N) and the Sunrise and Frenchmen

Fig. 2. Physiography of the study area. A: topography; B: geology (simplified after Castor and Faulds, 2001); C: surface map (simplified from Nellis Dunes surface units map by B. McLaurin, D. Goossens and B. Buck, unpublished).

A Topography

B Geology

Quaternary	Coarse clastic
Quaternary/Tertiary fans	Volcanics of Calville Bay
Limestone	Red sandstone unit
Gypsum	River Mountains volcanics
Marl	Horse Springs Formation
Fine-grained clastic	Pre-Tertiary

C Major surface units

sands and sand affected areas

silt/clay areas

rock-covered areas

bedrock

Mountains (to the S), on a surface generally tilting from the NE to the SW. A detailed topographic map of the area is shown in Fig. 2A. The southwestern and southeastern parts of the area are generally flat, tilting slightly to the SW. The central part shows a more complex topography, with various SW–NE-oriented valleys separated by elongated ridges and (especially in the NW) plateaus. The incision of these valleys is more prominent in the south (25–35 m) than in the north (usually about 15–20 m). In the northeastern corner the area becomes slightly mountainous, with several SW–NE ridges separating narrow valleys up to 50 m deep (Fig. 2A). These ridges culminate at about 60–80 m above the surrounding landscape. Their altitude is around 850 m a.s.l., whereas the lowermost parts of Nellis Dunes Recreational Area (SW and SE corners) are situated at about 605 m a.s.l.

2.3. Geology

Except from the mountains in the northeast, which are of pre-Tertiary age and consist of limestone, Nellis Dunes Recreational Area is mainly composed of incised fan remnants and exposed late Tertiary and Quaternary sediments (Fig. 2B). The late Tertiary deposits are believed to be the Muddy Creek Formation (~10 to 5 Ma). They consist of 2–50 m thick limestone that overlies, and is partially interbedded with, a marl sequence as much as 10 m thick. The marl locally contains rock fragments of limestone, and thin gypsite layers (Castor and Faulds, 2001). A fine-grained sandy sequence underlies the limestone and marl. In the SW and SE corners of the field Quaternary to late Tertiary alluvial fans and fan remnants occur. The center of the southern portion of the field area is characterized by an extended zone of dune sands, which cover the Tertiary deposits. Although much of the sand is generally only a few dm thick, many highly active barchanoid ridges (oriented NW–SE) are present. These ridges can be up to 250 m long and are one of the most popular off-road driving zones in the area.

2.4. Soils

Soil development is negligible in the areas of bedrock exposure (these include the badlands of exposed Muddy Creek Formation) and active sand dunes. In these regions the surficial characteristics are controlled by the underlying geology or dune sand characteristics. In the remaining areas (primarily the fan remnants), the soils are characterized by thin (0–10 cm), platy, alkaline, A and Av (vesicular) horizons containing low amounts of organic matter. Vesicular A (Av) horizons are almost always associated with desert pavements. Well-developed soils occur primarily in the southeast and southwestern portions of the field area. They contain pedogenic accumulations of calcium carbonate at depth (~15 to >100 cm), forming calcic and petrocalcic horizons. In many areas (especially in the western portion of the field) the surface horizons are eroded exposing the calcic or petrocalcic horizons at the surface. In these areas, much of the surface gravels can be composed of broken fragments of the petrocalcic horizons. Pedogenic gypsum and other salt minerals are negligible or absent. Soils in the study area are classified as Typic Haplocalcids, Calcic Petrocalcids and Typic Torriorthents.

2.5. Climate

Nellis Dunes Recreational Area is located in the northeastern part of the Mojave Desert and is thus characterized by an arid climate. Summers are hot and dry, with temperatures over 40 °C, whereas winters are mild, with an average daily maximum in January around 13.5 °C. Average annual temperature is 19.5 °C (Lazaro et al., 2004). Precipitation is low, partly because of the rain shadow created by the Sierra Nevada Range and the Spring Mountains west of Las Vegas, which protect the area from large western synoptic systems (BLM, 2004). Average annual precipitation is 105 mm, but may vary sub-stantially between years. Monthly average precipitation ranges from

2 mm in June to 14 mm in February. Scattered thunderstorms typically occur at the end of July and the beginning of August.

Average annual wind speed is about 4.1 m s^{-1} in Las Vegas but is slightly higher in the Nellis Dunes. Winds blow mainly from the NE from November to March and from the south in April–September. During episodes of strong winds blowing sand and dust are a common phenomenon in Nellis Dunes Recreational Area although the aeolian activity varies considerably over the field. The dunes and loose silty deposits in the west are much more active than the stabilized silt, gravel and bedrock substrata in the east. In the west, visibility during periods of heavy sediment transport can be as low as a few m.

2.6. Surface units

Nellis Dunes Recreational Area is characterized by a large number of surface units. At least 17 types of surfaces were recognized during this study. Surface type is a key factor in the off-road experiments reported here and more information is therefore given below.

2.6.1. General classification

Four major surface classes can be distinguished in the Nellis Dunes area (see also Fig. 2C):

1. Sands and sand-affected areas: active or stabilized sands, with or without rock fragments and/or vegetation;
2. Silt/clay areas: loose and slightly stabilized silt/clay deposits, with or without rock fragments;
3. Rock-covered areas: stabilized silty or sandy silty deposits with rock fragments on top, desert pavements over a silty sublayer, bedrock, and petrocalcic horizons;
4. Drainage areas: active drainages in sand and silt areas, and gravelly drainages.

Fig. 2C shows that the sand units are present in the center of the southern portion of the test field, whereas the silt/clay areas predominantly occur in the NW. Rock-covered areas encompass almost all of the eastern part of the Nellis Dunes field. Bedrock is mainly outcropping in the northeastern mountains. Drainages (not shown on the map because they are too numerous to be all displayed) occur all over the field except in the central sand dunes, and mature drainages are also absent in the northeastern mountains because of the limited size of the hydrological catchments in this area.

A description of each surface type is given in the next sections. Information on mechanical and sedimentological properties is presented in Table 1. Fig. 3 shows a photograph of each surface type for comparisons to other regions.

2.6.2. Sand and sand-affected areas

2.6.2.1. Surface unit 1.1: dunes with no vegetation. Active sand dunes and sand sheets with no vegetation. The depth of the active sand layer varies from a few dm to several m. Sparse rock fragments may outcrop locally where the sand layer is very shallow. Surface crusts are absent.

2.6.2.2. Surface unit 1.2: dunes with vegetation. Dune sands with sparse and isolated shrubs. The sand is active and there is no surface crust. Small coppice dunes may be present. Rock fragments may occur on the surface, but rock cover is low and does not affect the deflation.

2.6.2.3. Surface unit 1.3: disturbed sand surfaces. Mixture of loose and active sand, rock fragments and (eventually) bedrock. This unit typically occurs in areas where shallow sands cover a substratum of petrocalcic horizons and/or bedrock and disturbance by human activity is high (parking lots, road shoulders, etc.).

2.6.2.4. Surface unit 1.4: patchy layers of sand over silty/rocky subsoil. These surfaces show an almost continuous layer of sand (depth

Table 1
Characteristics of the 17 surface units

Surface unit	Soil texture										Rock fragments			Surface crust	Surface resistance		Vegetation
	>2000 μm	1000–2000 μ	710–1000 μm	500–710 μm	250–500 μm	180–250 μm	105–180 μm	63–105 μm	<63 μm	Median grain diameter (fraction <500 μm)	Rock cover (on surface)		Rock content (>2 mm in upper 15 mm)	Presence	Normal resistance	Tangential resistance	Vegetation cover
											total area	non-vegetated area only					
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(μm)	(%)	(%)	(%)		(kg cm^{-2})	(kg cm^{-2})	(%)
Sands and sand-affected surfaces																	
1.1	00.01	0.01	0.01	0.03	12.03	58.77	26.97	2.12	0.07	209.98	0.0	0.0	0.01	No	0.136	0.051	0.5
1.2	13.86	0.61	0.23	0.17	4.06	21.14	48.32	10.50	0.88	181.50	4.3	4.6	13.86	No	0.143	0.134	8.7
1.3	49.74	2.76	0.99	8.75	3.01	4.10	24.25	5.15	1.08	178.45	54.6	54.9	49.74	No	0.159	0.171	0.5
1.4	40.84	0.60	0.16	0.22	0.44	2.01	45.42	8.43	1.44	153.21	23.6	28.3	40.84	No	0.149	0.244	18.3
1.5	10.77	6.70	2.14	1.70	7.58	9.03	46.69	11.77	2.35	152.20	4.3	4.3	10.77	Yes	0.615	0.710	1.0
Silt/clay surfaces																	
2.1	19.62	2.46	1.19	1.69	7.97	13.35	18.02	26.20	8.63	155.94	3.4	4.1	19.62	Yes	0.210	0.780	16.8
2.2	24.45	5.86	3.70	3.96	9.81	7.47	15.13	15.29	10.95	52.35	11.3	11.6	24.45	Yes	0.207	0.689	2.1
2.3	31.85	18.67	9.31	10.21	14.34	4.45	4.56	3.09	3.02	122.54	2.7	2.7	31.85[a]	Yes	0.117	0.364	0.0
2.4	42.31	1.65	1.17	1.76	8.79	12.79	21.21	7.40	2.88	192.97	31.7	31.9	42.31	Yes	1.112	1.940	0.5
Rock-covered surfaces																	
3.1	74.40	1.80	1.26	0.88	2.97	2.95	8.19	5.77	1.47	117.26	94.9	97.8	74.40	No[b]	NA[b]	NA[b]	3.0
3.2	46.68	5.01	2.30	1.97	5.15	5.32	20.38	9.24	3.31	135.91	64.4	75.6	46.68	Yes	1.109	1.451	14.4
3.3	32.29	1.63	0.55	0.50	1.12	2.07	41.07	18.37	2.34	139.98	32.6	40.1	32.29	Yes	1.152	0.969	18.4
3.4	20.81	2.73	0.83	1.19	6.33	9.38	38.43	16.90	2.90	156.68	22.6	25.1	20.81	Yes	0.218	0.560	10.1
3.5	99.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	84.79	94.3	98.5	99.99	No[c]	NA[c]	NA[c]	4.4
Drainage surfaces																	
4.1	94.77	1.24	0.38	0.36	1.11	0.55	1.25	0.25	0.07	211.10	97.9	97.9	94.77	No[b]	NA[b]	NA[b]	0.0
4.2	63.93	4.50	1.24	1.10	6.43	10.02	9.82	2.17	0.56	229.08	76.0	76.0	63.93	No	0.085	0.127	0.0
4.3	60.54	6.27	2.45	2.37	11.42	9.44	5.10	1.40	0.64	202.23	35.8	47.0	60.54	Yes	1.452	1.219	21.4

[a] Particles >2 mm consist of aggregates of silt.
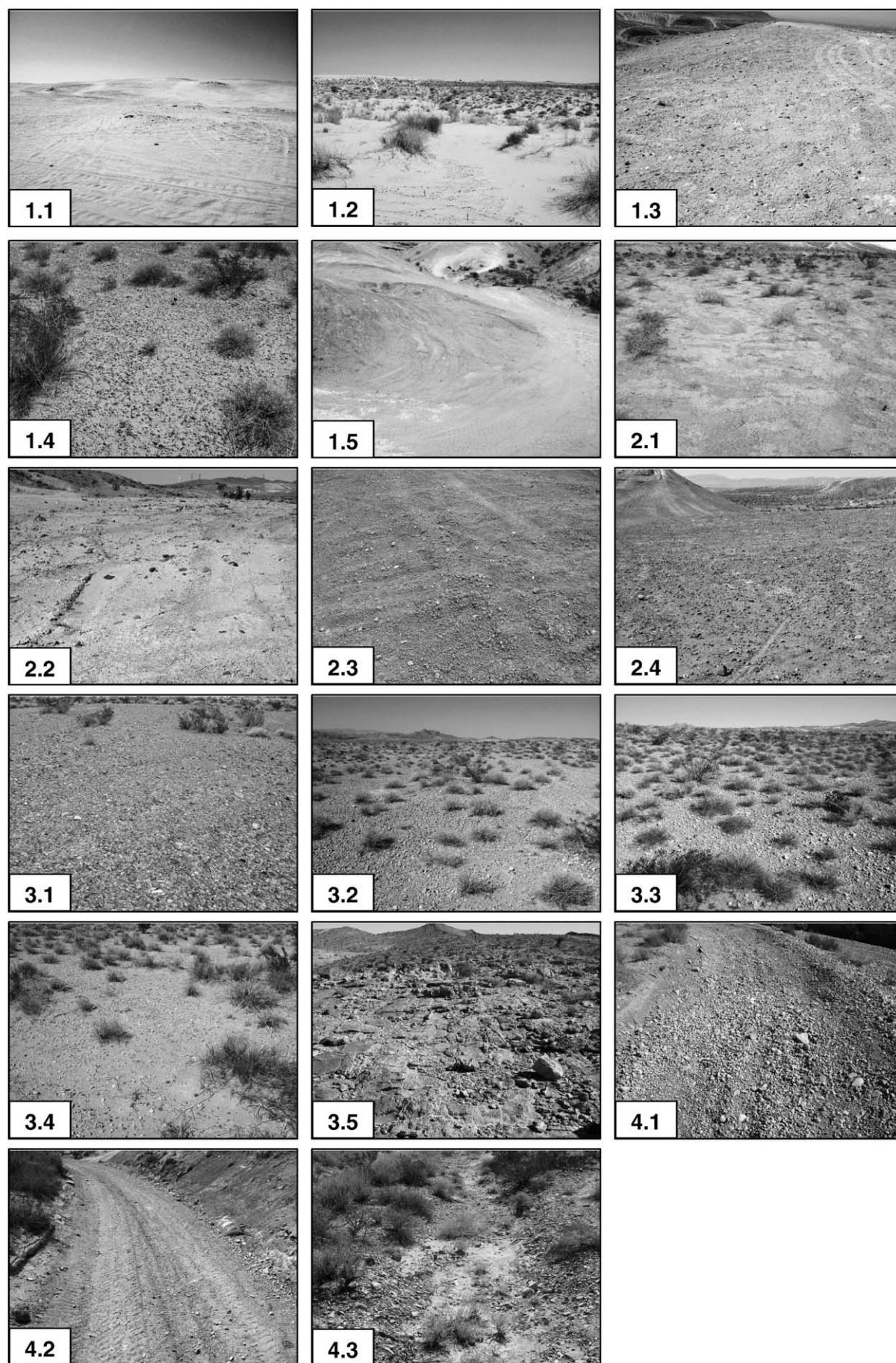[b] Desert pavement.
[c] Bedrock.

Fig. 3. Photographs of the 17 surface units selected for this study.

usually a few cm), with many pebbles outcropping. There is no surface crust; the sand is active and small juvenile dunes may locally occur.

2.6.2.5. Surface unit 1.5: outcrops of very fine sand and coarse silt. These outcrops may occur in badlands and on steep slopes, but also on plateaus. In Nellis Dunes Recreational Area they typically have a yellow color, but this may be different in other areas. These surfaces are almost free of vegetation and are usually stabilized by a silty sandy crust.

2.6.3. Silt/clay areas

2.6.3.1. Surface unit 2.1: silt/clay with crust. These surfaces usually occur near drainage channels in silt areas. The sediment is predominantly composed of silt and shows a continuous crust. Some vegetation (isolated shrubs) is typical. A few rock fragments may occur, but they remain sparse.

2.6.3.2. Surface unit 2.2: silt/clay with gravel. Mixture of silt and gravel, but with considerably more silt than gravel. A surface crust may be present although many areas are not crusted. These surfaces do not occur in drainage areas but are typically located on steep hill slopes and plateau escarpments.

2.6.3.3. Surface unit 2.3: aggregated silt deposits. Silt/clay surfaces where the particles are bound in aggregates up to 5 mm in diameter. The percentage of free particles is low. A surface crust is common but the crust may be disturbed or even absent. These surfaces are entirely devoid of vegetation and look like a typical moon landscape.

2.6.3.4. Surface unit 2.4: disturbed silt surfaces. Mixture of non-crusted silt, rock fragments and (eventually) bedrock. They occur in areas where the surface has been disturbed by human activity and are the silt equivalent of surface unit 1.3.

2.6.4. Rock-covered areas

2.6.4.1. Surface unit 3.1: desert pavements. Well developed and mature desert pavements over a (usually silty) subsoil. The rock fragments are partially embedded in the silt and rock cover density is close to 100%. Vegetation (shrubs) may locally occur, but most desert pavements are devoid of any vegetation.

2.6.4.2. Surface unit 3.2: rock-covered surfaces with silt/clay zones. The top layer is composed of silt and contains many rock fragments. The areas in between the rock fragments show a continuous and permanent surface crust. Vegetation (shrubs) typically covers 10–15% of the surface. These surfaces occur anywhere in the landscape and are the dominant surface unit in the Nellis Dunes area, especially in the E (Fig. 2C).

2.6.4.3. Surface unit 3.3: rock-covered surfaces with sandy loam. These surfaces resemble surface unit 3.2, but the top layer contains small amounts of sand. The sand has been blown in from nearby sand areas. In the Nellis Dunes field they typically occur in silt areas located closely to the sand dunes.

2.6.4.4. Surface unit 3.4: rock-covered surfaces with encrusted sand. This type of surface is similar to the 3.2 and 3.3 surfaces but is almost exclusively composed of sand, with only small amounts of silt. However, the silt, together with the sand, is able to create a continuous crust. This crust is much weaker than the silt crusts of surface units 3.2 and 3.3 (Table 1). Vegetation (shrubs) is common.

2.6.4.5. Surface unit 3.5: bedrock and/or petrocalcic horizons. Outcropping bedrock and areas of outcropping petrocalcic horizons.

The percentage of rock cover is close to 100%. Only near a few sparse shrubs and in deep cracks may some silt have accumulated in the course of time.

2.6.5. Active drainages

2.6.5.1. Surface unit 4.1: gravelly drainages. Active drainages with almost pure gravel. In the Nellis Dunes area these surfaces typically occur in the channels of the major drainages. The gravel is almost free of sand, silt and clay and its cover percentage is close to 100%.

2.6.5.2. Surface unit 4.2: gravel and sand drainages. Active drainages with a mixture of sand and gravel. They occur in sand areas, more especially in the smaller sized valleys, and also in the upstream zone of the larger drainages where there is insufficient water to wash the sand. Vegetation is usually absent.

2.6.5.3. Surface unit 4.3: gravel and silt/clay drainages. Active drainages with a mixture of silt and gravel. They are the silt equivalent of surface unit 4.2, except that many of them have considerable vegetation (usually shrubs). Silt/gravel drainages without vegetation also occur, especially in first-order channels in badlands.

3. The Nellis Dunes experiment: procedure

All experiments were performed on dry soils. Moisture content was always very close to zero: relative humidity in the region is extremely low, evaporation rates very high, and no rains occurred during at least 3 weeks prior to the measurements.

3.1. Vehicle types tested

Three types of vehicle were tested in the experiment: the 4-wheeler (quad), the dune buggy, and the dirt bike (motorcycle). These vehicles represent more than 99% of all off-road vehicles driving in the Nellis Dunes. Fig. 4 shows a photograph of each vehicle. All vehicles used in the test were equipped with standard type tires. Tire tread was not considered as a parameter in this study.

3.2. Field procedure

Much attention was paid to seeking adequate experimental locations, to ensure reliable as well as representative data. A track long enough to attain high speeds was selected on each surface unit. For safety reasons, and also to ensure homogeneous emissions near the measurement spot, only straight sections without curves were selected.

Two vertical poles with 4 sediment traps each were erected 1.5 m from the centre line of the track (Fig. 5). BSNE samplers (Fryrear, 1986) were used to collect the dust. We used BSNE samplers because of their relatively large inlet area (10 cm^2), and also because efficiency of the BSNE is known for various grain size fractions (Goossens and Offer, 2000; Goossens et al., 2000; Sharratt et al., 2007). All data were corrected for the efficiency of the traps. BSNEs were installed at the following heights: 0.25 m, 0.50 m, 0.75 m and 1.00 m. Drivers were asked to drive at approximately 1 m from the poles. Observations during the runs revealed that the height of the dust cloud was always between 1.0 and 1.5 m near the poles; dust clouds were thus adequately sampled during the experiment.

Measurements were done on days when the wind blew perpendicular to the road. During 95% of the runs the two poles were installed on the same side of the road to ensure adequate collection. A few cases occurred where the wind speed was so low that the dust was emitted to both sides of the road; if that happened one of the poles was put on the other side of the road, or if that was not possible, the amounts of dust recorded by the traps were doubled. Careful observations were
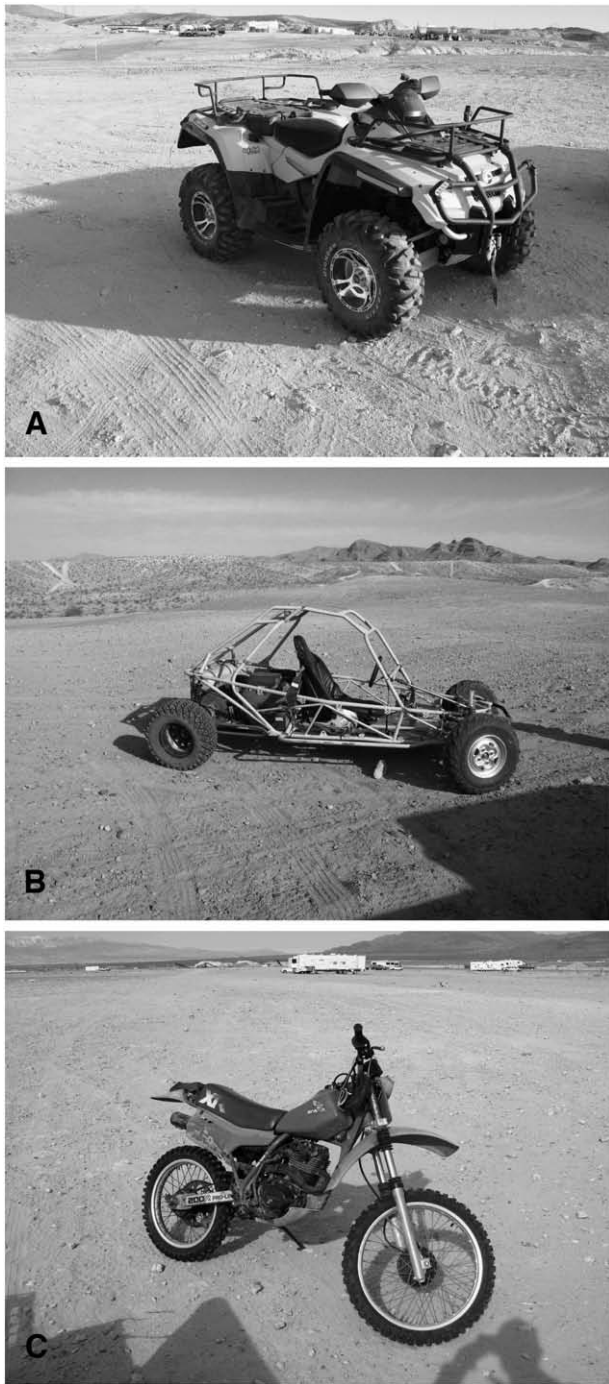
Fig. 4. The three vehicle types tested. A: 4-wheeler (quad); B: dune buggy; C: dirt bike (motorcycle).

made of the wind during each run to determine the correction, and all results were later corrected for low wind speed conditions (but this was only necessary for a few tests).

Dirt bikes are normally being driven at higher speeds than 4-wheelers and dune buggies. To ensure representative results it was decided to select the driving speeds according to the type of vehicle. Three speeds were selected for each vehicle at each location, and although the drivers were able to drive with the same speeds on most locations there were a few cases where they had to drive somewhat slower for safety reasons. A portable electronic Schwinn speedometer (Pacific Cycle Inc., Madison, WI, USA) was attached to each vehicle to measure the exact speed during each run. For the dirt bike the speeds

were usually around 32, 43 and 56 km h^{-1}; for the 4-wheeler around 28, 36 and 48 km h^{-1}, and for the dune buggy, around 24, 32 and 40 km h^{-1}.

Between 22 and 30 runs were made for each combination of driving speed, vehicle and surface type. Altogether 3684 runs were made, 144 experiments in total. For safety reasons (very rough and mountainous terrain), and also because of the absence of loose sediment on the surface, no measurements were carried out on surface unit 3.5 (bedrock). This does not really pose a problem for this study because the emission will be virtually equal to zero on these surfaces.

After each experiment clean BSNEs were installed on the poles. Used BSNEs were immediately stored in a closed box to prevent subsequent contamination of the traps.

Sediment samples were taken at all locations from the road and also from undisturbed topsoil to investigate how long-term off-road driving affects the topsoil.

3.3. Laboratory procedure

After each field test all BSNEs were taken to a closed laboratory for dust collection. Samples were collected with a brush, and with great care to not affect the grain size distribution. All samples were weighed with an analytical Ohaus Explorer balance (Ohaus Corporation, Pine Brook, NJ, USA). Precision of the measurements was 0.0001 g.

To determine the proportion of individual grain size fractions all samples were analyzed with a Malvern Mastersizer 2000 grain size analyzer (Malvern Instruments Ltd., Malvern, UK). Emissions were calculated for grain size fractions between 2.5 μm and 100 μm. No calculations were made for particles >100 μm since, in the current study, we are only interested in the emission of suspendable particles. All data for the coarser grain size fractions remain available for future research, or for comparison, if required.

3.4. Calculation of the emission

Two possibilities exist to calculate the emission. The most common procedure is to calculate the emission as a flux, i.e. mass of sediment emitted per unit surface and per unit time (expressed in, for example, kg m^{-2} s^{-1}). However, in the case of off-road driving this option is not very useful because the area of road surface prone to emission depends on the number of wheels of the vehicle, the width of the wheels, and the surface structure of the wheels and the road: only where the wheels effectively touch the road direct emission will occur (in reality the problem is more complex because the intersurfaces can also experience emission due to the turbulence created by the driving vehicle). This makes it difficult to determine the exact size of the

Fig. 5. Photo of the set-up of dust poles and dust traps during a dirt bike run.
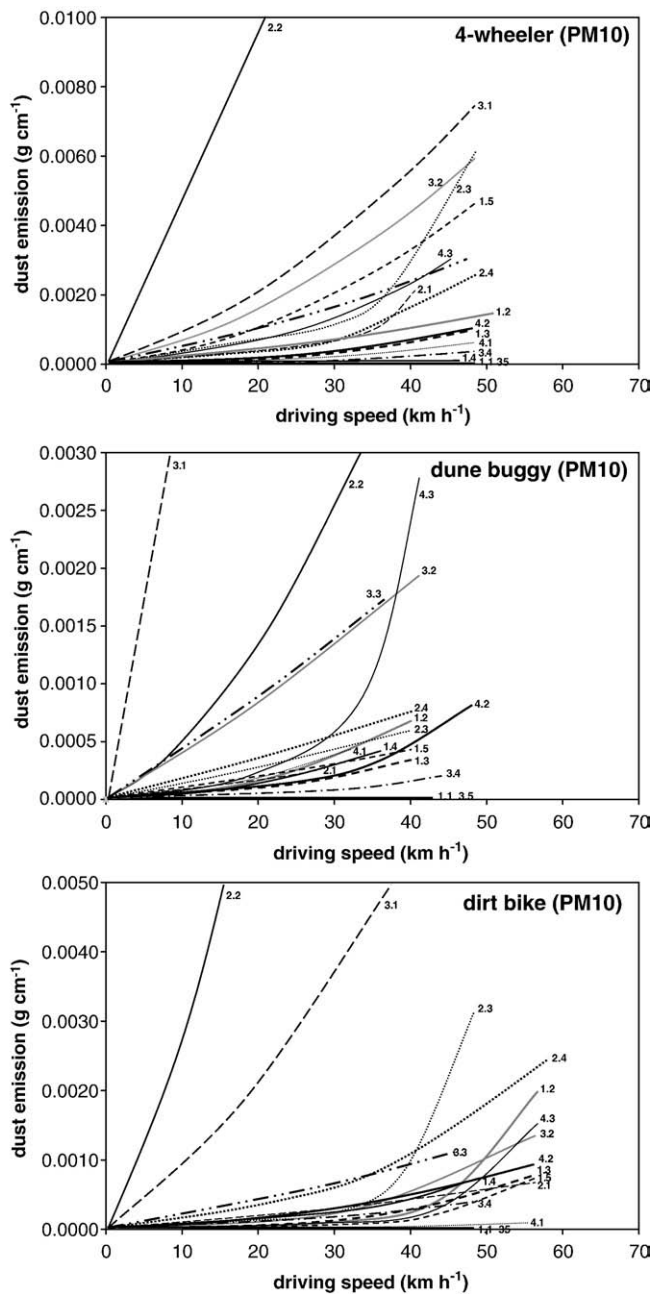
Fig. 6. Basic emission curves for PM10.

zero height) to the top of the cloud. In the case of aeolian transport of particles <100 μm the horizontal transport flux (*Fh*) usually decays with height (*z*) according to the function $Fh = az^b$, where coefficient *a* and exponent *b* are determined empirically (Buschiazzo and Zobeck, 2005). The vertical transport profile in the dust cloud during the Nellis Dunes experiments showed a similar decay for all experiments. However, for mathematical reasons no calculations of the profile down to $z = 0$ are possible when the power function above is used. Therefore the profile was described with a 4th order polynomial (for several experiments a 3rd order polynomial already gave an optimum fit). All curve fittings were carefully inspected in a graph before calculating any transport to ensure adequate fits, but there were no major problems.

The result of the calculation is the mass of dust transported through a 1-cm wide strip parallel to the road and with a height equal to the height of the cloud (very close to 1.5 m at the location of the poles in almost all experiments). Since there is no dust above the
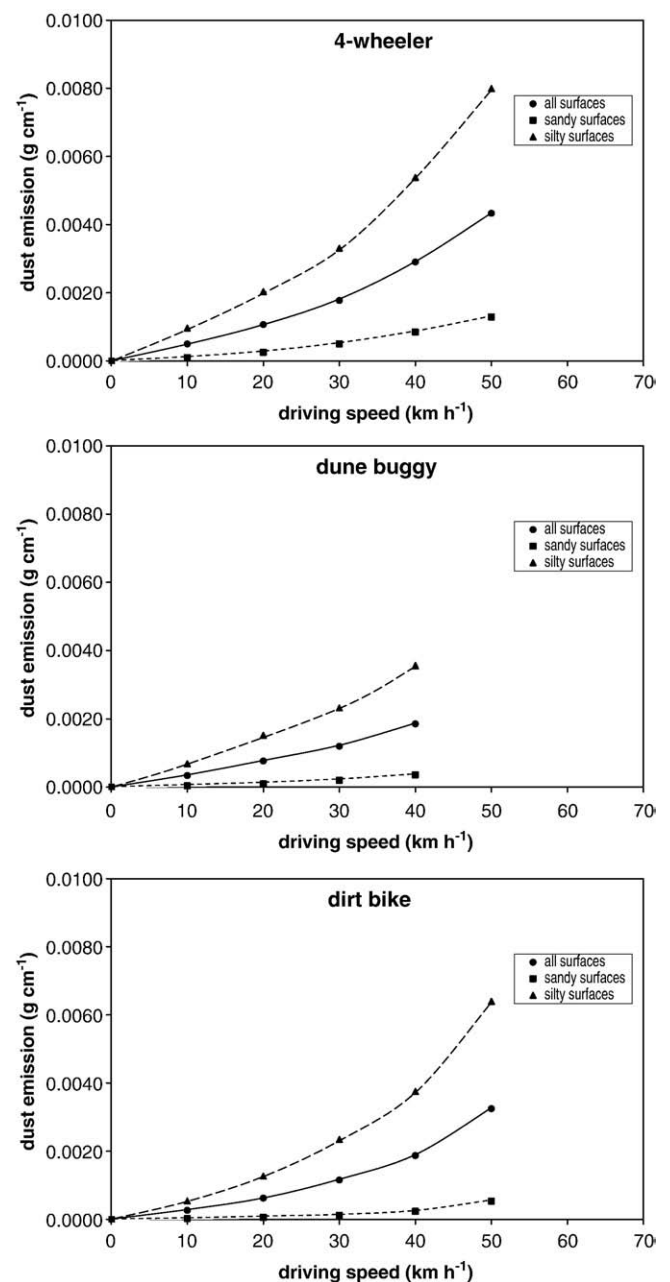
emission surface and, thus, of the emission flux. A much better option for off-road driving is to calculate the emission in terms of emitted mass per unit length (for example, kg of dust emitted per driven km). If the total length of a run is known, the total mass of dust emitted during that run can be calculated. Of course, for adequate estimations the emission rates should be known for various driving speeds, and information is needed on the speed (and its variation) during a run.

In this study emission is presented as emitted mass per unit length. The calculation procedure is as follows.

First, the amount of dust passing through the dust cloud is calculated at the height of each trap. By dividing the mass of dust caught by a trap through the trap's inlet area (10 cm² for a BSNE), and after correction for the trap's efficiency, the total transport (in g cm⁻²) at each trap height is calculated. Next, the total mass transported through a vertical strip 1 cm wide and parallel to the road is calculated by vertically integrating the dust profile from the road surface (i.e., at

Fig. 7. PM10 emission curves, grouped for the major surface classes.
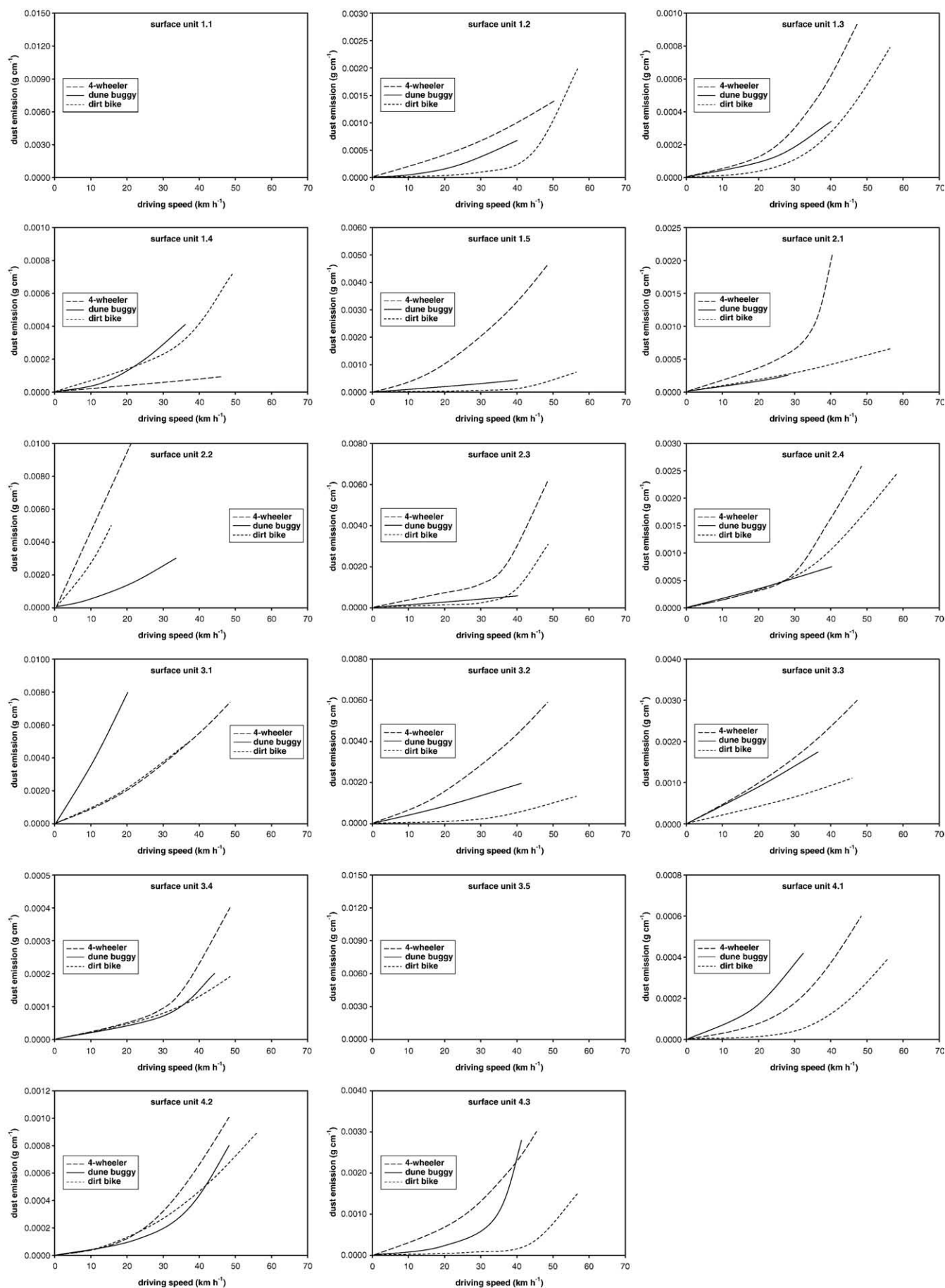
Fig. 8. PM10 emission curves for the individual surface types.

upper edge of the cloud, this corresponds to the total mass of dust emitted per unit length driven by the vehicle.

4. Results

4.1. PM10 emissions

For each combination of vehicle and surface type emission data are available for 4 speeds: the 3 speeds tested during the experiments and zero emission at zero driving speed (no wind erosion occurred during the measurements). Since the emission progressively increased with the driving speed, speed-emission curves could be constructed for all experiments. Fig. 6 shows the curves for the 51 combinations of vehicle and surface type for PM10. In order to not overload the graphs and keep the pictures readable the individual data points are not shown, but it should be emphasized that they are very close to the curves shown. For example, for the 4-wheeler graph (upper graph in Fig. 6) the correlation coefficient R is >0.95 for 16 of the 17 curves (even >0.98 for 14 of the curves), and its lowest value is still 0.89 (surface unit 1.2). The other graphs show similar correlations.

Although the shape and position of individual curves vary with vehicle and surface type the general trends in the figure are clear: highest emissions were always measured on surface units 2.2 (silt/clay with gravel) and 3.1 (desert pavements) whereas lowest emissions occurred on the uncrusted (or only weakly crusted) sandy surfaces (1.1, 1.2, 1.3, 1.4, 3.4) and the gravel and bedrock surfaces (3.5, 4.1). The thin surficial stone layer of the desert pavements (3.1) did not provide much protection against off-road driving (contrary to wind erosion). The silty surfaces (except 2.2 and 3.1) showed intermediate emission values.

To facilitate interpretations the data of Fig. 6 are replotted in Fig. 7, for the silty and sandy surfaces separately and also for the ensemble of all surface units. In addition, the emission values were calculated for identical driving speeds for all vehicles. Interpolation was used to calculate the emission at each particular speed. No data are shown for the dune buggy at driving speeds >40 km h^{-1} because the dune buggy was unable to reach such speeds during the experiments.

Fig. 7 shows that, on average, PM10 emission increased exponentially with the driving speed. As could be expected, the silty surfaces produced much more dust than the sandy surfaces. Also, emission varied considerably with the type of vehicle. Most PM10 was emitted by the 4-wheeler whereas, on average, the dune buggy and the dirt bike emitted almost equal amounts of PM10 despite the dune buggy having more wheels than the dirt bike (4 instead of 2).

Fig. 8 shows the speed-emission curves for the 17 surface units separately. Although it is relatively easy to recognize the general trend (highest emission: 4-wheeler; intermediate emission: dune buggy; lowest emission: dirt bike) substantial differences occur for individual surface units, both with respect to the relative order of the vehicles and the rate of increase of emission with driving speed. These differences do not appear to be systematically related to a specific type of surface or vehicle but may occur anywhere in the data set (see Fig. 8), which makes it difficult to interpret them.

In Fig. 9 the data of Fig. 8 are replotted for the silty and sandy surfaces separately, and also for the ensemble of all surface units. Similar to Fig. 7 the data were recalculated to identical driving speeds to facilitate comparisons. The general trend is clear: most PM10 was emitted by the 4-wheeler, and this at all driving speeds. On average the dune buggy produced slightly more PM10 than the dirt bike, but from a driving speed of around 35 km h^{-1} the dirt bike seems to produce more PM10 than the dune buggy. This increased production is only discernable on silty surfaces; it does not seem to occur on sandy surfaces.

4.2. TSP emissions

Fig. 10 shows the speed-emission curves for all 51 combinations of vehicle and surface type, for the fraction <60 µm (defined in this study
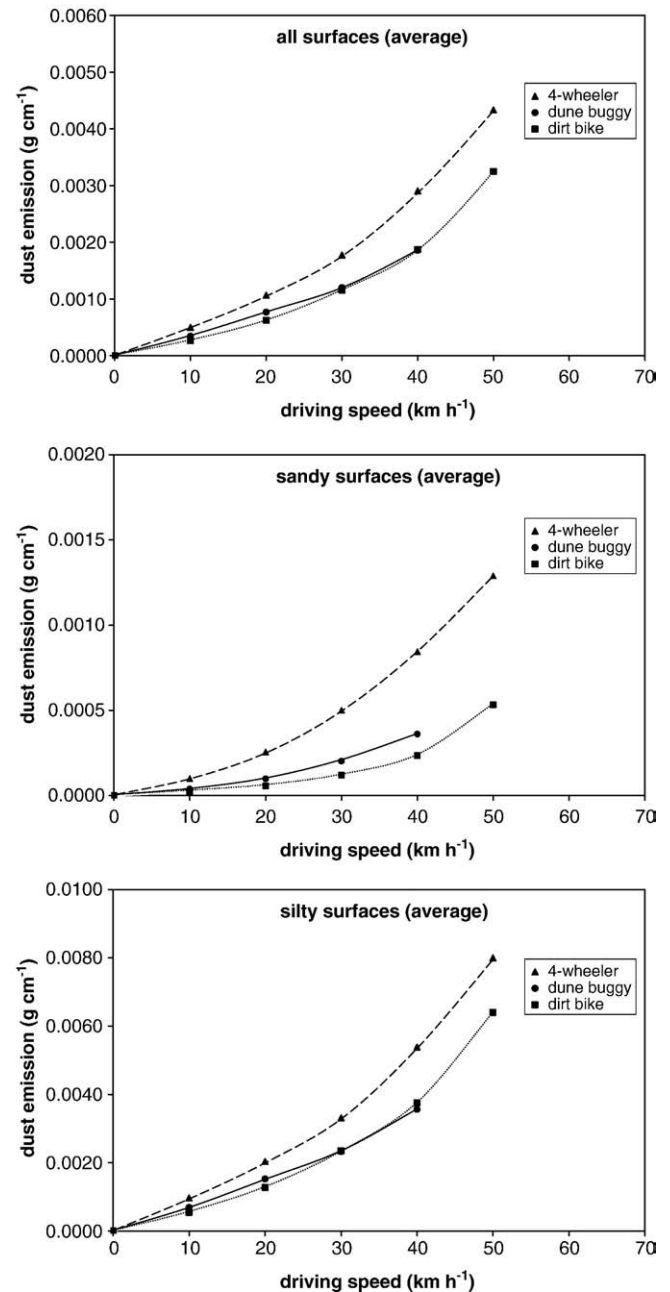

Fig. 9. PM10 emission curves, grouped for the 3 vehicles tested.

as TSP, or total suspendable particles). We used the 60-µm limit as a cut-off for TSP because it corresponds to the maximum size of those grains that will still be transported in short-term suspension during average conditions of wind speed and turbulence (Pye and Tsoar, 1990). It also nearly coincides with the upper diameter of silt (52 µm or 63 µm, depending on which criterion is used).

The general trends already observed in Fig. 6 also appear in Fig. 10: most dust was produced by surface units 2.2 (silt/clay with gravel) and 3.1 (desert pavements) whereas the sandy surfaces produced the least amounts of dust. Differences between the PM10 and TSP patterns exist for various surface units: a striking example are the 4.3 surfaces (silty drainages), which proportionally emit much more TSP than PM10. Less significant differences can be detected for several other surface units.

Averaging the data for the two major surface groups (silty and sandy surfaces) leads to TSP patterns that are similar to those for PM10
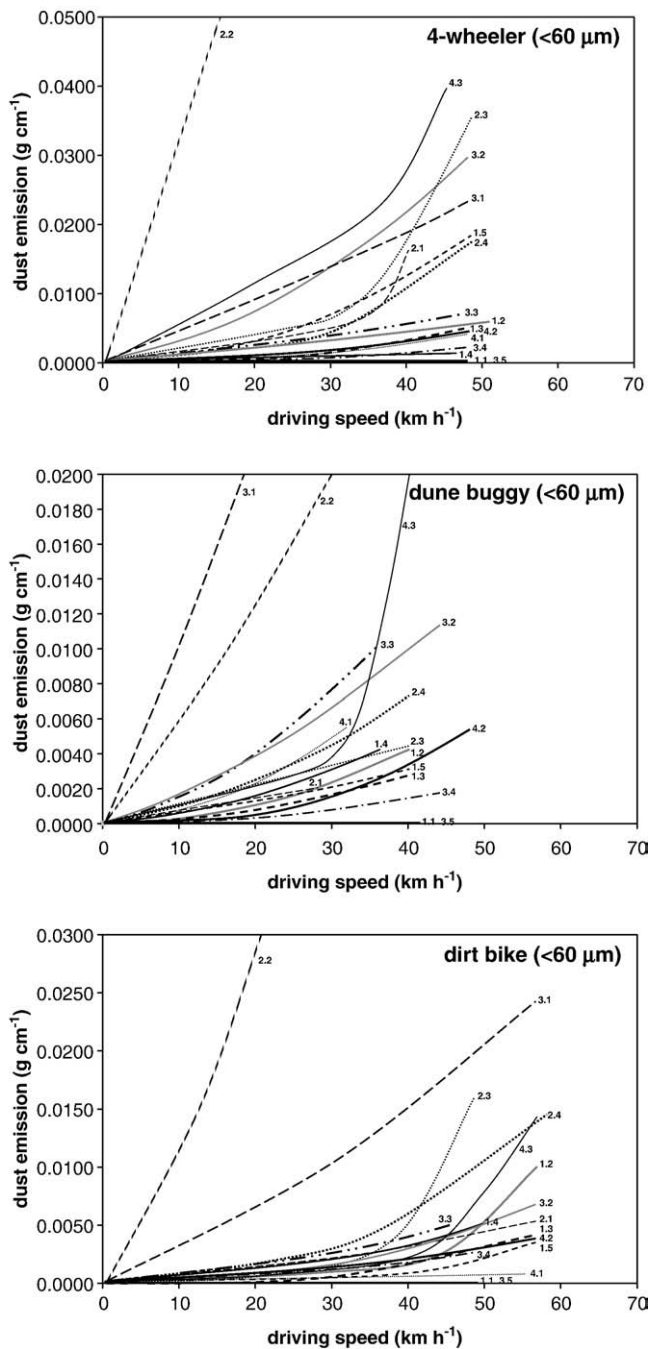
Fig. 10. Basic emission curves for TSP.

than PM10 compared to the other vehicles. No such trend was found for the silty surfaces.

5. Discussion

The data show that the amount of dust emitted by off-road vehicles may strongly vary depending on which type of vehicle is driving with what speed over what type of surface. This is quite understandable if we consider how the emissions are produced. Most unpaved roads consist of a graded and compacted roadbed usually created from the parent soil material (Gillies et al., 2005). The rolling wheels of the vehicle impart a force to the surface that pulverizes the roadbed material and ejects particles from the shearing force as well as by the turbulent vehicle waves (Nicholson et al., 1989). Previous studies have shown that the emission rate primarily depends on the vehicle speed (Nicholson et al., 1989; Etyemezian et al., 2003a,b), the fine particle content of the road (Cowherd et al., 1990; MRI, 2001), the vehicle
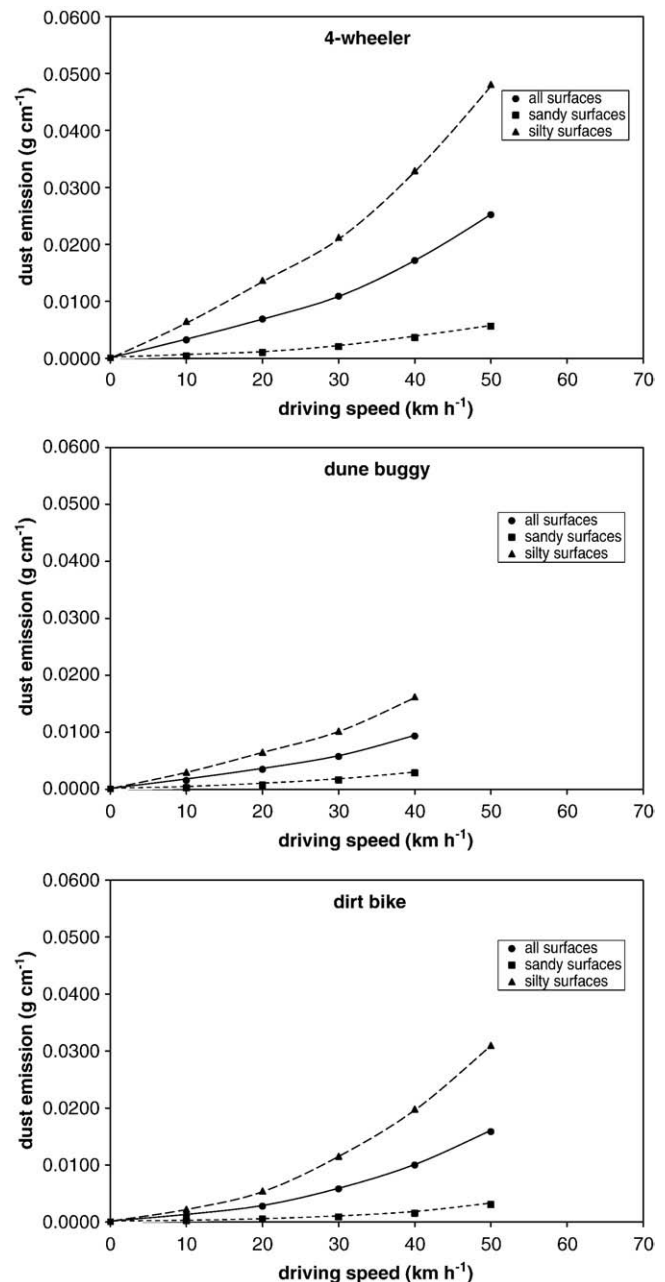

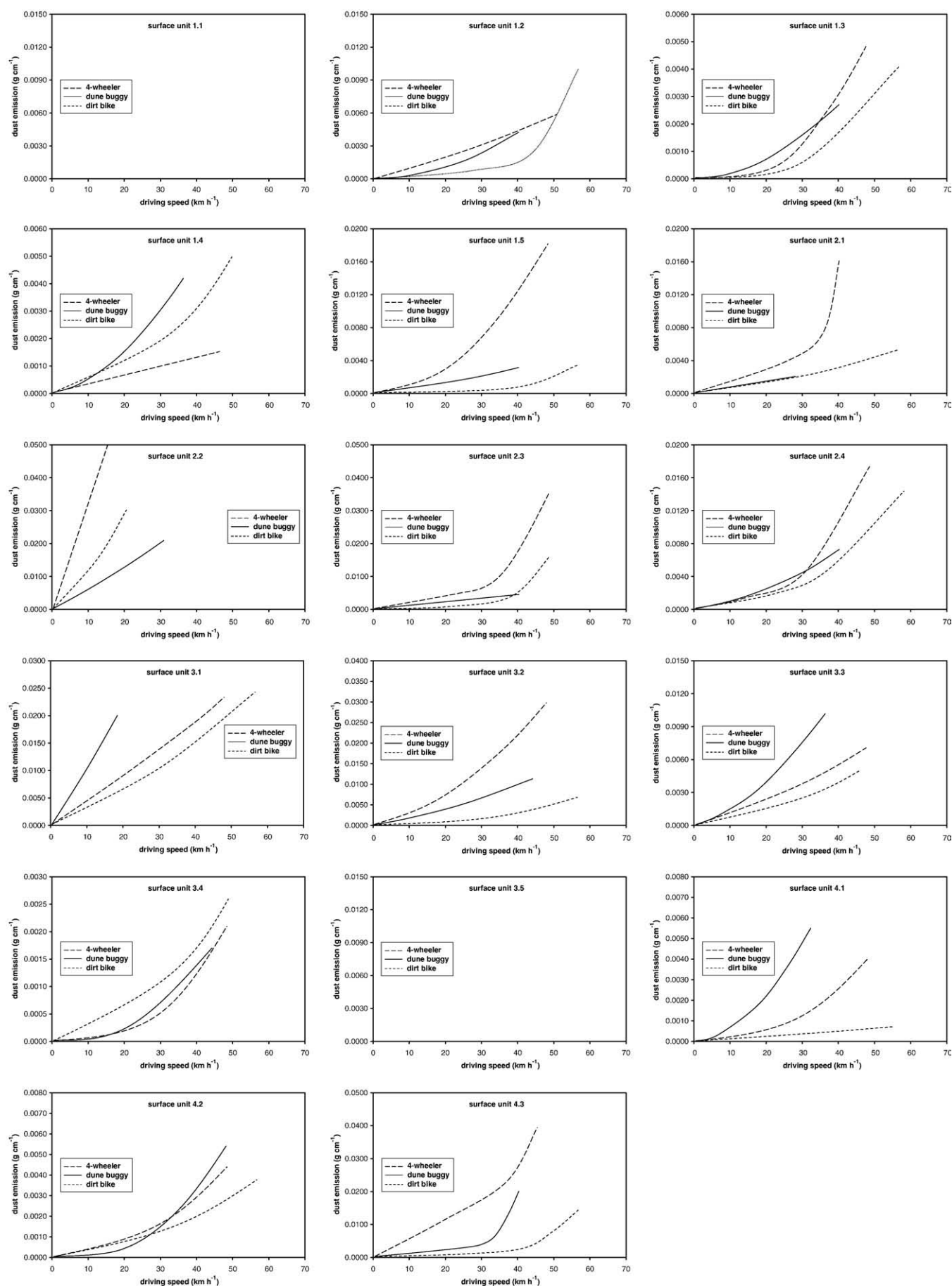Fig. 11. TSP emission curves, grouped for the major surface classes.

(Fig. 11). Not surprisingly silty surfaces produce much more TSP than sandy surfaces, for all 3 vehicles tested.

Plotting the speed-emission curves for individual surface units shows similar patterns as for PM10 (Fig. 12, and compare to Fig. 8). Differences do occur: examples are the dune buggy on surface unit 3.3 (rock-covered surfaces with sandy loam), and the 4-wheeler on surface unit 3.4 (rock-covered surfaces with encrusted sand). Also here, differences in the mutual behavior of the vehicles do not seem to be systematically correlated to surface type, as for PM10.

Replotting the data for the silt and sand classes (Fig. 13) leads to similar conclusions as for PM10. Most dust is produced by the 4-wheeler whereas, on average for all surface types, the dune buggy and the dirt bike produce almost equal amounts of dust. However, on sandy surfaces the dune buggy proportionally emits much more TSP

Fig. 12. TSP emission curves for the individual surface types.

Fig. 13. TSP emission curves, grouped for the 3 vehicles tested.

studies (e.g. Etyemezian et al., 2003b; Hussein et al., 2008). In a few cases the relationship was linear, as suggested by the US EPA (1995) formula. Linear relationships have also been reported by Gillies et al. (2005) and Hussein et al. (2008). The Nellis Dunes experiment did not show correlations between the type of increase (linear or exponential) and the surface or vehicle type.

The effects wheel and tire parameters (such as wheel diameter, wheel width and tire tread) have on dust emission have not yet been adequately quantified and these parameters do not appear in the emission equations currently in use. This study did not consider these parameters, but all vehicles used were equipped with standard-sized wheels and tires.

The large number of surface types tested in this study permit checking of the proposed relationship between emission and silt content of the road material. Samples were taken from the roads at the same locations where the emissions had been measured. The silt content (<60 μm) was determined with the Malvern Mastersizer 2000 instrument after the non-erodible fractions (>500 μm) had been removed by sieving. Plotting the emission (TSP) as a function of the silt percentage a more or less linear relationship is observed (Fig. 14), but there is considerable spread in the data. This is reflected by the coefficient of determination R^2, which, for the data in Fig. 14, equals only 0.43. The data in Fig. 14 are for the average driving speeds of the distinct vehicles. Looking at the R^2 values for individual speeds we find that the relationship between TSP emission and the silt content of the road becomes better as the driving speed increases. The R^2 values are: 0.27 (10 km h^{-1}), 0.30 (20 km h^{-1}), 0.34 (30 km h^{-1}), and 0.47 (40 km h^{-1}). No R^2 could be calculated for a speed of 50 km h^{-1} because the dune buggy was unable to attain this speed over the surface types tested. Therefore, driving speed is a crucial parameter in off-road driving and formulae calculating the emission *must* include it.

Fig. 15 shows the proportion of PM10 in the emitted TSP. The PM10 content does not seem to vary with the driving speed, regardless of which soil class (silt or sand) or vehicle type is considered. The graphs on the left also show that the proportion of PM10 in the total dust production is almost identical for the dune buggy and the dirt bike. This is unlike the 4-wheeler, for which the dust emitted contains more PM10 compared to the two other vehicles when driving over sandy surfaces, but less PM10 when driving over silty surfaces. As an average for *all* surfaces tested the PM10 content in dust emitted by a 4-wheeler is slightly lower than in dust emitted by a dune buggy or a dirt bike. A replot of the data for each distinct vehicle (Fig. 15, right) leads to the same conclusions. In general, for the surface units tested in the Nellis Dunes experiment the proportion of PM10 in the TSP is between 15 and 25%, slightly varying with vehicle and surface type, but not with driving speed.

weight (US EPA, 1996; MRI, 2001; US EPA, 2003), and the soil moisture content (Gillies et al., 2005). This is reflected by the 1995 US EPA AP-42 guidance document, where the emission is quantified as

$$EF = 0.161 \cdot s \cdot S \cdot W^{0.7} \cdot w^{0.5} \cdot \left(\frac{365-p}{365}\right)$$

where *EF* is the emission factor (g/vehicle kilometer traveled), *s* the silt content of the road material (%), *S* the vehicle speed (m s^{-1}), *W* the weight of the vehicle (Mg), *w* the number of wheels, and *p* the number of days per year with measurable precipitation (>0.25 mm). However, later versions (US EPA, 1999) no longer included the vehicle speed as a parameter in estimating emission factors for unpaved roads (Etyemezian et al., 2003b).

Vehicle speed is an important parameter, however, as is clearly demonstrated by the Nellis Dunes experiment. In most cases (combinations of vehicle type and surface unit) the increase of emission with vehicle speed was exponential, similar to what has been found in other
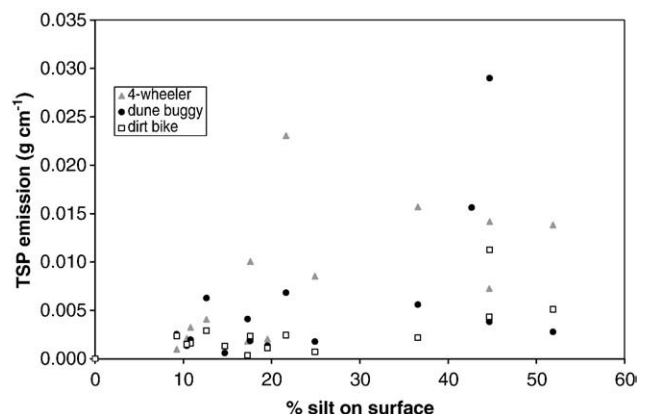

Fig. 14. Relationship between TSP emission rate and silt content of the road surface. Data points of the 4-wheeler and dirt bike for surface unit 2.2 are out of the vertical range and do not appear in the picture.
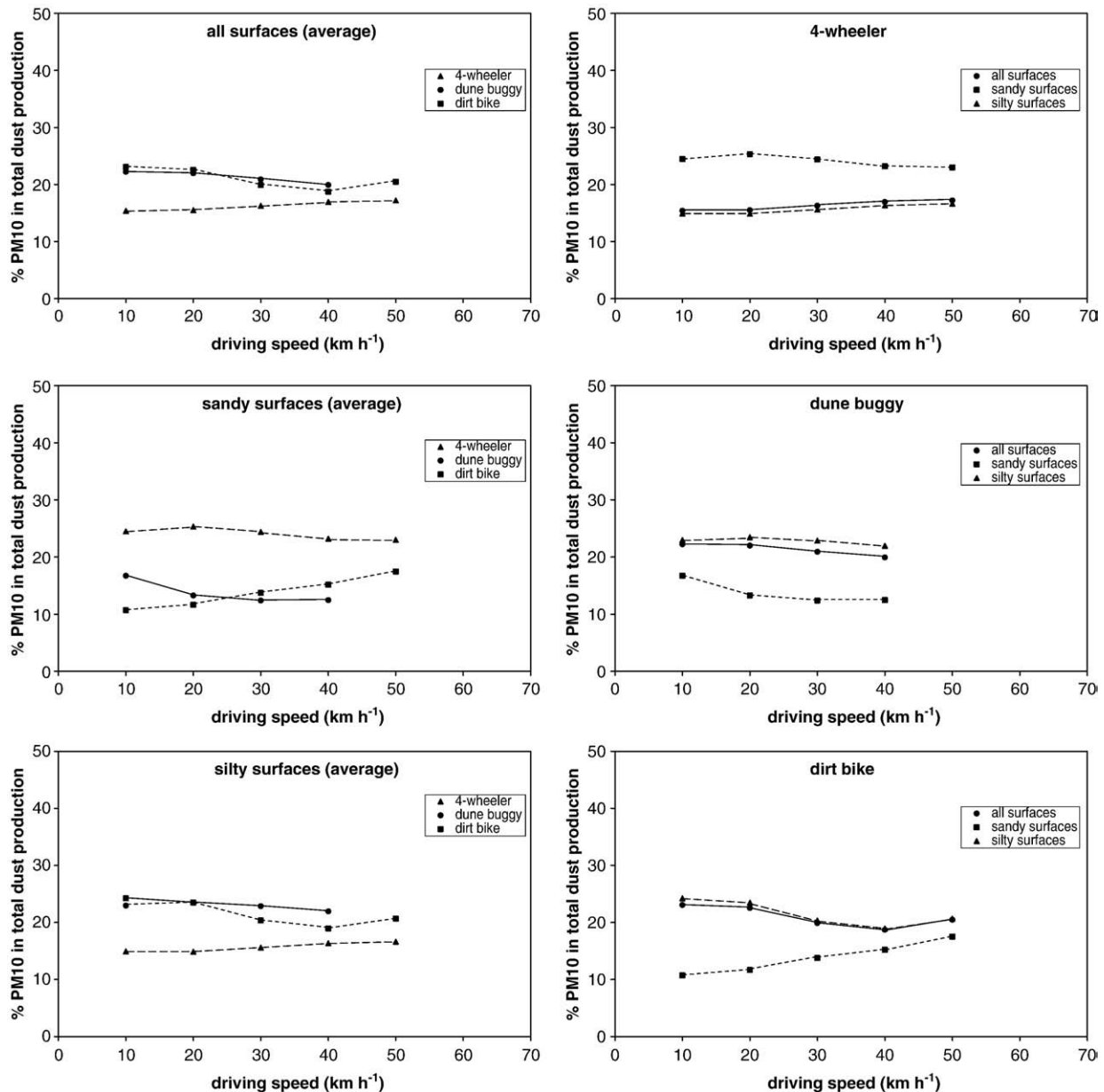
Fig. 15. Proportion of PM10 in TSP.

Fig. 16 shows the (average) median grain diameter (*D50*) of the emitted dust. As mentioned earlier, for safety and practical reasons it was not possible to drive with the same speeds over all surface units. Therefore, to be able to calculate average curves (such as in Fig. 16) the raw *D50* data were first plotted in a graph to check how *D50* varied with the driving speed. This was done for all surface units, and for all 3 vehicles. The data showed that *D50* did not vary substantially with the driving speed, and for those cases where a (slight) relationship was observed the relationship was almost linear. To reconstruct the *D50* for standard speeds (3 for each vehicle, see Fig. 16) we thus used linear interpolation (or, in a few cases, extrapolation).

Two conclusions can be derived from Fig. 16. First, the average size of the emitted dust (represented in this study by the average median grain diameter in the vertical dust profile, that is, in the dust cloud) remains almost constant as a function of the driving speed. A slight increase (coarser dust) with speed occurs for sand surfaces, but for silt surfaces a (similarly small) decrease occurs (Fig. 16, left). Secondly, the dust emitted by a dune buggy is finer than that emitted by a 4-wheeler or a dirt bike regardless over which class of soil (sand or silt) the

vehicle is driving. The 4-wheeler and dirt bike emit nearly evenly coarse dust. Replotting the data for the distinct vehicles (Fig. 16, right) leads to the same conclusions.

A comparison between the emitted dust and its parent material (on the road surface) is presented in Table 2. For most surface units the median grain diameter of emitted dust is smaller than that of the parent sediment: off-road driving preferentially removes the finest particles. Unless new fine particles can be supplied (for example, by a progressive incision of the road in the underlying substratum) the road surface will thus coarsen with time. An important exception to this are the surface units 2.2, 2.3 and 2.4, i.e. silty surfaces without, or with only a limited amount of vegetation. For these surfaces the median grain diameter of the emitted dust is almost equal to (or even slightly higher than) that of the road dust, i.e. roads on these surfaces do not get coarser by off-road driving.

Columns 4 and 5 in Table 2 show the PM10 content on the road and in the emitted dust, respectively. As could be expected, roads with higher PM10 produce PM10-rich dust. However, the PM10 content is always lower in the emitted dust compared to the parent soil (see
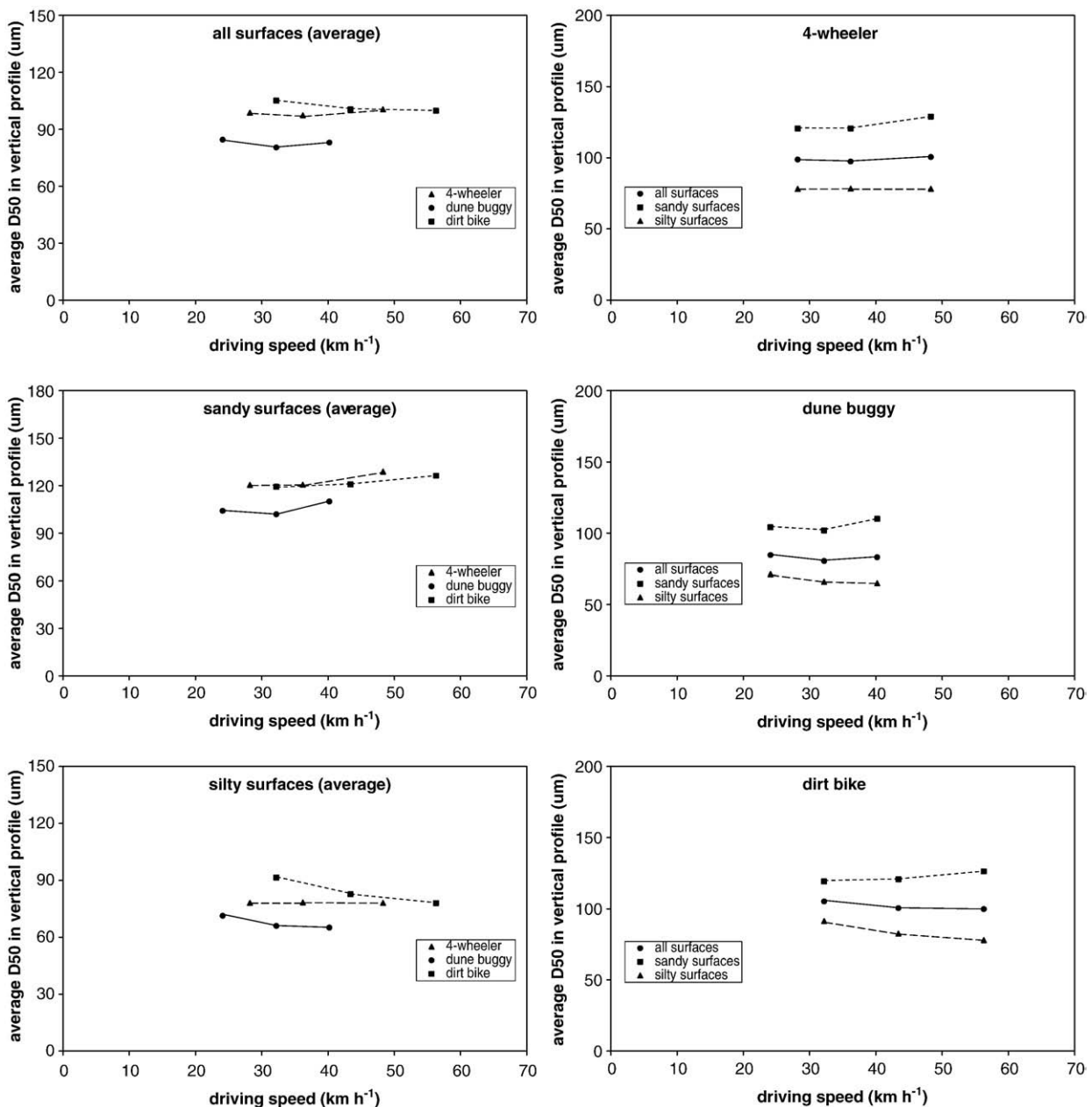
Fig. 16. Average median grain diameter (*D50*) of emitted dust as a function of driving speed.

right column in Table 2). The average value for all surface units (called in this study the E-factor, see Table 2) is only 0.57, or 57%. Therefore, off-road driving emits PM10 less efficiently than it emits the coarser fractions.

The Nellis Dunes data allow one to check for which grain size fraction(s) emission is most efficient. Calculating the E-factor for various grain size classes and displaying the results in a histogram (Fig. 17) we see that emission due to off-road driving is most efficient at a grain size of approximately 60 μm. This value is only slightly smaller than that for wind erosion, which is situated around 80 μm (Bagnold, 1941; Horikawa and Shen, 1960; Iversen and White, 1982). Fig. 17 also shows that the E-factor drops below unity from a grain size of approximately 25 μm — i.e. for grains <25 μm the emission process is not very efficient. Particle and interparticle forces (cohesion and adhesion) hamper the removal of the grains from the road surface.

It should be recalled that all numbers given above were derived for air-dry surfaces; for moist surfaces they will be substantially higher.

When driving off-road, drivers usually drive their vehicles over various types of surfaces. Also, they constantly change their speed due to local factors such as topography, curves in the road, local obstacles, etc. To get an idea of the amounts of dust produced during a realistic drive, various routes were selected in the Nellis Dunes area and the emission was calculated for typical drives along these routes. The following scenarios were calculated:

- Scenario 1: drive through a sandy area
- Scenario 2: drive through a silty area
- Scenario 3: drive through drainages
- Scenario 4: drive through mixed terrain

Fig. 18 shows the trajectories, plotted on the simplified surface unit map. Detailed information for each route is given in Table 3. For each scenario the emission was calculated for both PM10 and TSP, for all 3 vehicles tested, and for 5 driving speeds varying from 10 to 50 km h^{-1} (10 to 40 km h^{-1} for the dune buggy).

Table 2
Grain size characteristics of emitted dust compared to the parent sediment (average for all vehicle types and driving speeds tested)

Surface unit	$D50$ (µm)		PM10 content in total sediment (%)		PM10 in emitted sediment/PM10 on road surface
	Road surface	Emitted sediment	Road surface	Emitted sediment	
1.1	215	189	0.00	0.00	NA
1.2	196	118	4.23	2.32	0.55
1.3	175	101	5.92	2.78	0.47
1.4	157	102	3.72	1.77	0.48
1.5	164	88	7.64	6.76	0.88
2.1	117	83	4.78	3.41	0.71
2.2	73	69	11.05	6.12	0.55
2.3	57	72	13.08	6.63	0.51
2.4	71	70	8.27	6.39	0.77
3.1	98	80	24.45	8.67	0.35
3.2	96	65	14.37	7.61	0.53
3.3	143	101	6.46	4.03	0.62
3.4	165	109	5.04	2.56	0.51
3.5	NA	NA	NA	NA	NA
4.1	271	80	5.51	3.62	0.66
4.2	252	111	4.04	3.68	0.91
4.3	147	73	5.17	3.49	0.67
				Average (=E-factor)	*0.57*

Fig. 19 shows the results for PM10. The main conclusions are: 1) in all 4 scenarios the largest amounts of PM10 are produced by the 4-wheeler, followed by the dune buggy and the dirt bike; 2) the faster the vehicles are driving, the more PM10 they will emit; 3) typical amounts of PM10 emitted are as follows: for drives in sand areas: 30–40 g km^{-1}; for drives in silt areas: 150–200 g km^{-1} (100 g km^{-1} for dirt bikes); for drives through drainages: 30–40 g km^{-1}; and for drives in mixed terrain: 60–100 g km^{-1}.

Similar curves were calculated for TSP (Fig. 20). The pictures resemble those for PM10, although some slight differences can be observed for the dune buggy in the sand and drainage areas. The typical amounts of TSP emitted are: for drives in sand areas, about 200 g km^{-1}; for drives in silt areas, 600–700 g km^{-1} (1000–2000 g km^{-1} for 4-wheelers); for drives through drainages, 300–400 g km^{-1} (100–200 g km^{-1} for dirt bikes); and for drives in mixed terrain, 300–500 g km^{-1} (500–800 g km^{-1} for 4-wheelers).

For various reasons it is very difficult to estimate the total annual emission produced by off-road driving in the Nellis Dunes area. First, no exact data are available on the number of people visiting the area annually. A rough estimate of 285 000 was made by BLM (2004), but this number is highly uncertain because in southern Nevada the number of off-road drivers has increased by a factor of 4 in only a few years (Spivey, 2008). Second, no information is available on the distances driven by each driver during a visit. Third, both experienced and inexperienced drivers visit the area and the driving speeds thus show great variation. Fourth, no information is available on the number of drives conducted over each particular surface unit. Finally, most drivers stay in the western part of the area and rarely drive to the east since the two entrances to the field are both located in the west.

Despite these difficulties, an attempt was made to make a (very) crude estimate of the annual emission. The calculation was based on the following assumptions:

- 300 000 visitors per year
- drives over mixed terrain
- use of an "average" vehicle
- average driving speed during a run = 25 km h^{-1}
- average length of a run = 10 km

With these data the annual emission is 1253 tons year^{-1} (TSP) and 255 tons year^{-1} (PM10). The heavily driven areas encompass approximately 11 km^2; the remaining 26 km^2 are (very) much less driven. If we accept that all emission takes place in the heavily driven area (a realistic approximation in the case of the Nellis Dunes area), then the annual emission rates in the heavily driven area are 1.1 t ha^{-1} year^{-1} (TSP) and 0.2 t ha^{-1} year^{-1} (PM10). For an average driving speed of 35 km h^{-1} the numbers are 2.0 t ha^{-1} year^{-1} (TSP) and 0.4 t ha^{-1} year^{-1} (PM10), and for an average driving speed of 40 km h^{-1}, which is still very realistic, 2.5 t ha^{-1} year^{-1} (TSP) and 0.5 t ha^{-1} year^{-1} (PM10). These rates are of the same order of magnitude as those for wind-induced emission in many wind-erosion sensitive areas on the globe (Xuan et al., 2000; Goossens and Gross, 2002). Therefore, despite of the high uncertainty in the calculations it is reasonable to state that off-road driving can be a significant source of dust.

6. Conclusions

The experiments in the Nellis Dunes area show that off-road driving emits significant amounts of dust. This is true for PM10 dust as well as for coarser dust. However, the amounts emitted vary greatly with the type of sediment and the characteristics of the surface over which the vehicle is driving. For evident reasons sandy soils produce less dust than silty soils. However the high internal variability within mapped units (rock content, presence of vegetation, contamination of the top layer with locally blown in sediment, etc.) can also significantly affect emission rates. Using only a single soil parameter (such as the percentage of silt, as in the 1995 US EPA AP-42 formula) is thus insufficient to describe the effect of soil on dust emission.

As already reported in many previous studies the emission rates strongly depend on the driving speed. However, the Nellis Dunes experiment did not show systematic correlations between the normalized rate of increase of emission with speed and surface type. Similar surfaces can show different rates, which makes it difficult to model the emissions. Field measurements on the spot remain necessary for obtaining adequate data in each particular case.

Of the three types of vehicles tested, the 4-wheeler produced the largest amounts of dust, followed by the dune buggy and the dirt bike. It may be worth recalling that in many areas the dirt bike is able to drive faster than the dune buggy (and, sometimes, the 4-wheeler). Also, the dust emitted by a dune buggy is somewhat finer than that emitted by a 4-wheeler or a dirt bike.

Dust emitted by off-road driving is finer than the parent sediment on the road surface. Off-road driving thus results in a progressive coarsening of the top layer on the road, except for silty surfaces with no, or almost no, vegetation. For these surfaces there is no substantial difference in the median grain diameter of the emitted dust compared to the road dust. Off-road driving will not alter the average grain size of these roads.

Removal of particles by off-road driving is most efficient for grain sizes around 60 µm. For particles <25 µm the efficiency (in physical
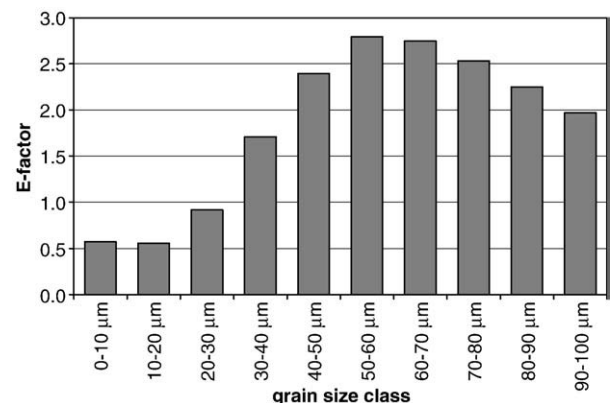

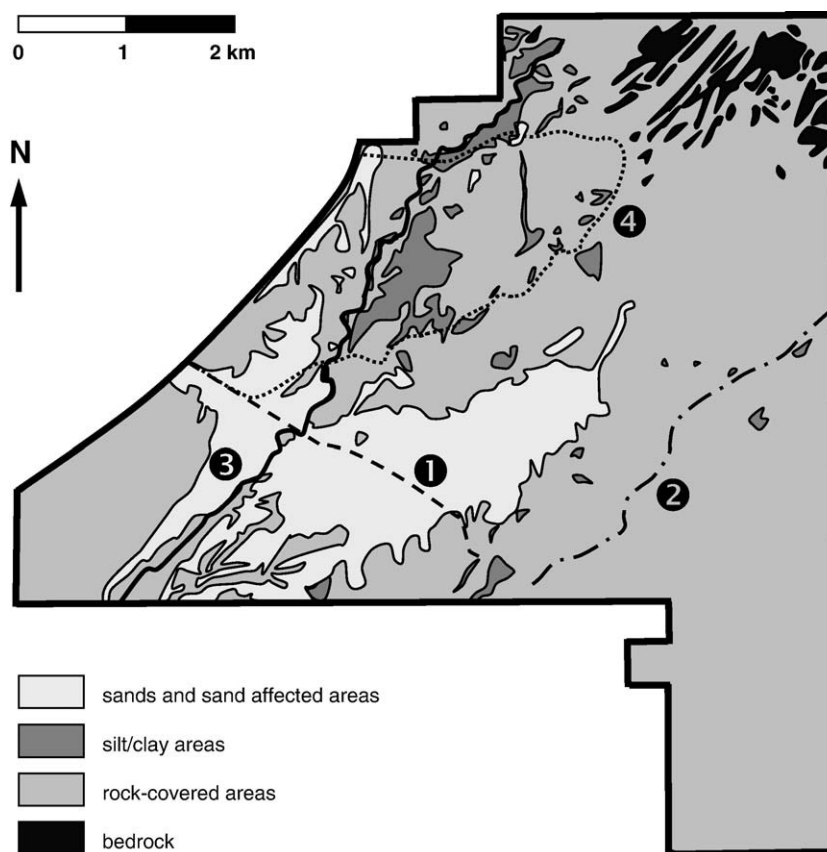**Fig. 17.** E-factor for various grain size classes of road dust.

Fig. 18. Trajectories of the 4 driving scenarios, superimposed on the simplified surface map. 1: Scenario 1 (sandy area); 2: Scenario 2 (silty area); 3: Scenario 3 (drainages); 4: Scenario 4 (mixed terrain).

terms) of the process becomes very low: cohesion and adhesion forces hamper emission of the grains. These numbers were derived for air-dry surfaces; for moist surfaces they will be substantially higher. It should be noted, however, that the finest particles (PM10, or even PM5) have most impact on human health.

Realistic emission rates for off-road driving on dry surfaces with 4-wheelers, dune buggies and dirt bikes are: drives in sandy areas, 30–40 g km^{-1} (PM10) and 150–250 g km^{-1} (TSP); drives in silty areas, 100–200 g km^{-1} (PM10) and 600–2000 g km^{-1} (TSP); drives in drainages, 30–40 g km^{-1} (PM10) and 100–400 g km^{-1} (TSP); and drives in mixed terrain, 60–100 g km^{-1} (PM10) and 300–800 g km^{-1} (TSP).

It was difficult to make (even very crude) estimates of the annual amount of dust emitted in the Nellis Dunes area by off-road driving because of the lack of information on the number of drivers, the length of each drive and the specific routes followed. However, calculations based on realistic values for these criteria indicate that emission by off-road driving can be of the order of several t ha^{-1} year^{-1}, which is comparable to wind erosion. In areas with stabilized surfaces (areas with an undisturbed surface crust, for instance) off-road driving might emit even more dust than wind erosion does. Much depends on how intense the area is driven by the vehicles, how stable the undisturbed surfaces are, and what types of vehicle are used. Heavy vehicles such as cars and trucks, which were not tested in this study, produce even

Table 3
Characteristics of the driving scenarios tested

| Scenario 1: sand area			Scenario 2: silt area			Scenario 3: drainage area			Scenario 4: mixed area		
Surface unit	Distance driven		Surface unit	Distance driven		Surface unit	Distance driven		Surface unit	Distance driven	
	m	% in drive		m	% in drive		m	% in drive		m	% in drive
1.1	225	6.62	2.2	11	0.27	4.1	4070	51.95	1.2	125	1.50
1.2	1157	34.03	3.1	264	6.43	4.2	1590	20.29	1.3	889	10.67
1.3	714	21.00	3.2	3654	88.97	4.3	2175	27.76	1.4	429	5.15
1.4	925	27.21	4.1	57	1.39				1.5	154	1.85
3.2	343	10.09	4.3	121	2.95				2.1	164	1.97
4.2	29	0.85							2.3	1239	14.88
4.3	7	0.21							2.4	146	1.75
									3.1	157	1.89
									3.2	3654	43.88
									3.3	861	10.34
									4.1	321	3.85
									4.2	7	0.08
									4.3	182	2.19
Total drive	3400	100.00	Total drive	4107	100.00	Total drive	7835	100.00	Total drive	8328	100.00
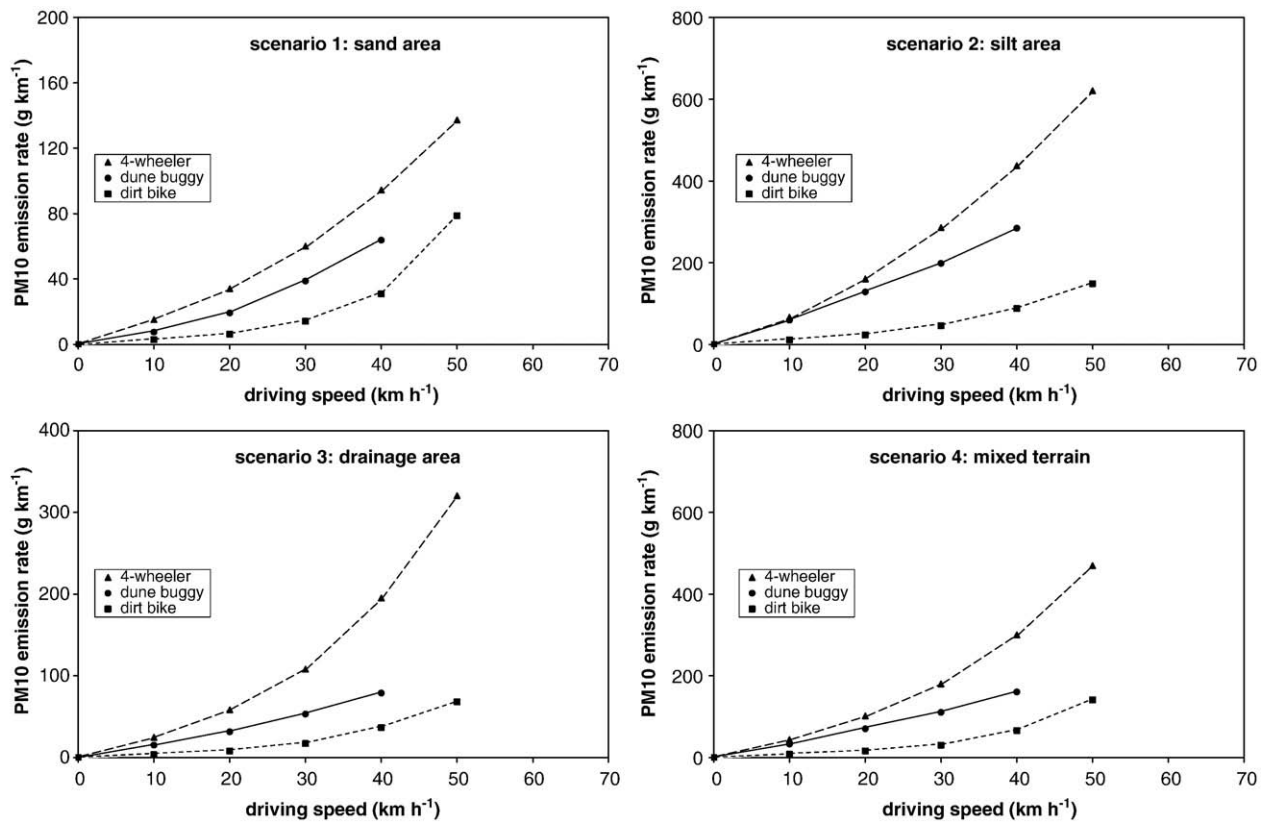
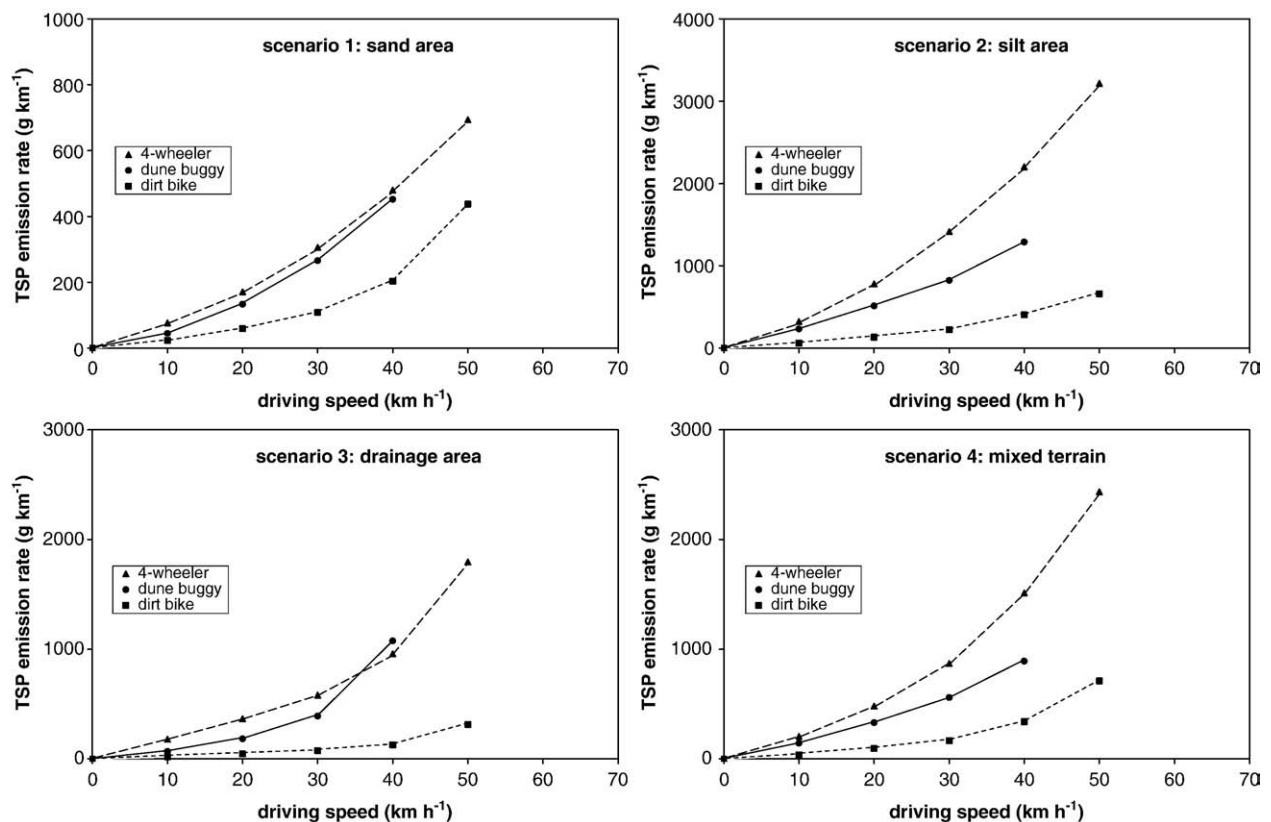**Fig. 19.** PM10 emission rates for the 4 scenarios tested.

Fig. 20. TSP emission rates for the 4 scenarios tested.

more dust than the vehicles used in this study (4-wheelers, dune buggies and dirt bikes).

References

Agbenin, J.O., 2001. The status and fluxes of alkali and alkaline-earth metals in a savanna Alfisol under long-term cultivation. Catena 45, 313–331.

Algharaibeh, M.A. 2000. Effect of influx of eolian materials on soil formation. Ph.D. Thesis, University of Arizona, USA.

Antoine, D., Nobileau, D., 2006. Recent increase of Saharan dust transport over the Mediterranean Sea, as revealed from ocean color satellite (SeaWiFS) observations. Journal of Geophysical Research 111, D12214. doi:10.1029/2005JD006795.

Ashbaugh, L.L., Matsumura, R.T., James, T., Carvacho, O.F., Flocchini, R., 1996. Modeling PM-10 dust emissions from field harvest operations. In: MacFarland, A., Curtit, K., Jacobson, L. (Eds.), Proc. Int. Conf. on Air Pollution from Agricultural Operations, Kansas City, Missouri, USA. Midwest Plan Service, Ames, Iowa, pp. 155–160 (MWPS C-3).

Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Methuen, London.

Baker, A.R., Kelly, S.D., Biswas, K.F., Witt, M., Jickells, T.D., 2003. Atmospheric deposition of nutrients to the Atlantic Ocean. Geophysical Research Letters 30, 2296. doi:10.1029/2003GL018518.

Baker, J.B., Southard, R.J., Mitchell, J.P., 2005. Agricultural dust production in standard and conservation tillage systems in the San Joaquin Valley. Journal of Environmental Quality 34, 1260–1269.

BLM, 2004. Las Vegas Valley Disposal Boundary, Final Environmental Impact Statement and Record of Decision, Chapter 3: Affected Environment. Las Vegas Bureau of Land Management, Las Vegas, Nevada.

Buschiazzo, D.E., Zobeck, T.M., 2005. Airborne horizontal mass flux calculated with different equations. Proc. 2005 ASAE Annual Meeting, Tampa, Florida, USA. Paper No. 052049.

Cassar, N., Bender, M.L., Barnett, B.A., Fan, S., Moxim, W.J., Levy, H., Tilbrook, B., 2007. The southern ocean biological response to aeolian iron deposition. Science 317, 1067–1070.

Castor, S.B., Faulds, J.E., 2001. Post-6 Ma limestone along the southeastern part of the Las Vegas Valley shear zone, southern Nevada. In: Young, A., Spamer, E.E. (Eds.), Colorado River. Origin and Evolution. Grand Canyon Association, Grand Canyon, Arizona, pp. 77–79.

Chase, Z., Paytan, A., Johnson, K.S., Street, J., Chen, Y., 2006. Input and cycling of iron in the Gulf of Aqaba, Red Sea. Global Biogeochemical Cycles 20, GB3017. doi:10.1029/2005GB002646.

Chen, Y., Siefert, R.L., 2004. Seasonal and spatial distributions and dry deposition fluxes of atmospheric total and labile iron over the tropical and subtropical North Atlantic Ocean. Journal of Geophysical Research 109, D09305. doi:10.1029/2003JD003958.

Clausnitzer, H., Singer, M.J., 1996. Respirable-dust production from agricultural operations in the Sacramento Valley, California. Journal of Environmental Quality 25, 877–884.

Cowherd, C., Englehart, P., Muleski, G.E., Kinsey, J.S., Rosbury, K.D., 1990. Control of Fugitive and Hazardous Dusts. Noyes Data Corp., Park Ridge, New Jersey.

Du, M., Yonemura, S., Shen, Z., Shen, Y., Wang, W., Yamada, Y., Maki, T., Kawashima, S., Inoue, L., 2005. Tillage effects on aeolian dust emission in bare agricultural fields at Dunhuang, China. Journal of Agricultural Meteorology 60, 503–506.

Duce, R.A., Tindale, N.W., 1991. Atmospheric transport of iron and its deposition in the ocean. Limnology and Oceanography 36, 1715–1726.

Eglinton, T.I., Eglinton, G., Dupont, L., Sholkovitz, E.R., Montluçon, D., Reddy, C.M., 2002. Composition, age, and provenance of organic matter in NW African dust over the Atlantic Ocean. Geochemistry Geophysics Geosystems 3, 1050. doi:10.1029/2001GC000269.

Etyemezian, V., Kuhns, H., Gillies, J., Chow, J., Hendrickson, K., McGown, M., Pitchford, M., 2003a. Vehicle-based road dust emission measurement: III — effect of speed, traffic volume, location, and season on PM10 road dust emission in the Treasure Valley, ID. Atmospheric Environment 37, 4583–4593.

Etyemezian, V., Kuhns, H., Gillies, J., Green, M., Pitchford, M., Watson, J., 2003b. Vehicle-based road dust emission measurement: I — methods and calibration. Atmospheric Environment 37, 4559–4571.

Fryrear, D.W., 1986. A field dust sampler. Journal of Soil and Water Conservation 41, 117–120.

Funk, R., Reuter, H.I., 2004. Dust production from arable land caused by wind erosion and tillage operations. Proc. Int. Symp. on Sand and Dust Storm, Beijing, China. Abstract No. 64.

Ganor, E., Foner, H.A., 2001. Mineral dust concentrations, deposition fluxes and deposition velocities in dust episodes over Israel. Journal of Geophysical Research 106, 18431–18438.

Gill, T.E., Cahill, T.A., 1992. Playa-generated dust storms from Owens Lake. In: HallJr. Jr., C.A., Doyle-Jones, V., Widawski, B. (Eds.), The History of Water: Eastern Sierra Nevada, Owens Valley, White Inyo Mountains. University of California Press, Los Angeles, pp. 63–73.

Gill, T.E., Westphal, D.L., Stephens, G., Peterson, R.E., 2000. Integrated assessment of regional dust transport from west Texas and New Mexico, spring 1999. Proc. 11th Joint Conference on the Applications of Air Pollution Meteorology with the Air and Waste Management Association, Long Beach, California, USA, pp. 370–375.

Gillette, D.A., Clayton, R.N., Mayeda, T.K., Jackson, M.L., Sridhar, K., 1978. Tropospheric aerosols from some major dust storms of the southwestern United States. Journal of Applied Meteorology 17, 832–845.

Gillies, J.A., Watson, J.G., Rogers, C.F., DuBois, J.C., Chow, J.C., Langston, R., Sweet, J., 1999. Long term efficiencies of dust suppressants to reduce PM10 emissions from unpaved roads. The Journal of the Air and Waste Management Association 49, 3–16.

Gillies, J.A., Etyemezian, V., Kuhns, H., Nikolic, D., Gillette, D.A., 2005. Effect of vehicle characteristics on unpaved road dust emissions. Atmospheric Environment 39, 2341–2347.

Gobbi, G.P., Barnaba, F., Ammannato, L., 2007. Estimating the impact of Saharan dust on the year 2001 PM10 record of Rome, Italy. Atmospheric Environment 41, 261–275.

Goossens, D. 2004. Wind erosion and tillage as a dust production mechanism on north European farmland. In: Goossens, D., Riksen, M. (Eds.), Wind Erosion and Dust Dynamics: Observations, Simulations, Modelling. ESW Publications, Department of Environmental Sciences, Erosion and Soil and Water Conservation Group, Wageningen University, Wageningen, pp. 15–40.

Goossens, D., Gross, J., 2002. Similarities and dissimilarities between the dynamics of sand and dust during wind erosion of loamy sandy soil. Catena 47, 269–289.

Goossens, D., Offer, Z.Y., 2000. Wind tunnel and field calibration of six aeolian dust samplers. Atmospheric Environment 34, 1043–1057.

Goossens, D., Offer, Z.Y., London, G., 2000. Wind tunnel and field calibration of five aeolian sand traps. Geomorphology 35, 233–252.

Goossens, D., Gross, J., Spaan, W., 2001. Aeolian dust dynamics in agricultural land areas in lower Saxony, Germany. Earth Surface Processes and Landforms 26, 701–720.

Goudie, A.S., 2002. Dust storms in the Middle East. Bulletin de la Classe des Sciences (Académie Royale des Sciences, des Lettres et des Beaux-Arts de Belgique) 6, 379–399.

Griffin, D.W., Garrison, V.H., Herman, J.R., Shinn, E.A., 2001. African desert dust in the Caribbean atmosphere: microbiology and public health. Aerobiologia 17, 203–213.

Griffin, D.W., Kubilay, N., Kocak, M., Gray, M.A., Borden, T.C., Shinn, E.A., 2007. Airborne desert dust and aeromicrobiology over the Turkish Mediterranean coastline. Atmospheric Environment 41, 4050–4062.

Herut, B., Krom, M., 1996. Atmospheric input of nutrients and dust to the SE Mediterranean. In: Guerzoni, S., Chester, R. (Eds.), The Impact of Desert Dust Across the Mediterranean. Kluwer, Dordrecht/London, pp. 349–358.

Hesse, P.P., 1994. The record of continental dust from Australia in Tasman Sea sediments. Quaternary Science Reviews 13, 257–272.

Horikawa, K., Shen, H.W. 1960. Sand Movement by Wind Action. United States Army, Corps of Engineers, Beach Erosion Board, Technical Memorandum TM-119.

Hussein, T., Johansson, C., Karlsson, H., Hansson, H.-C., 2008. Factors affecting non-tailpipe aerosol particle emissions from paved roads: on-road measurements in Stockholm, Sweden. Atmospheric Environment 42, 688–702.

Ilaiwi, M., El Asskar, M., 1998. Dust, dust storms and environmental degradation in the Syrian steppe. Proc. Int. Symp. on Sand and Dust Storms, WMO Technical Document, vol. 864, pp. 263–282.

Iversen, J.D., White, B.R., 1982. Saltation threshold on Earth, Mars and Venus. Sedimentology 29, 111–119.

Kuhns, H., Etyemezian, V., Green, M., Hendrickson, K., McGown, M., Barton, K., Pitchford, M., 2003. Vehicle-based road dust emission measurement: II — effect of precipitation, wintertime road sanding, and street sweepers on inferred PM10 emission potentials from paved and unpaved roads. Atmospheric Environment 37, 4573–4582.

Lazaro, M.A., Chang, Y.-S., Kuiper, J.A., Kotamarti, V.R., James, D.E., Brazao, R., Pulugurtha, S. 2004. Cumulative Las Vegas Valley Air Quality Modeling Assessment of Ongoing Bureau of Land Management (BLM) Federal Land Disposition Actions within the BLM Disposal Boundary. Report prepared for the Bureau of Land Management (BLM), University of Chicago and University of Nevada Las Vegas.

Marcus, M.G., Brazel, A.J., 1992. Summer dust storms in the Arizona Desert. In: Janelle, D.G. (Ed.), Geographical Snapshots of North America. Guilford Press, New York, pp. 411–415.

Marx, S.K., Kamber, B.S., McGowan, H.A., 2005. Estimates of Australian dust flux into New Zealand: quantifying the eastern Australian dust plume pathway using trace element calibrated ^{210}Pb as a monitor. Earth and Planetary Science Letters 239, 336–351.

Matsumura, R.T., Flocchini, R.G., Cahill, T.A., Carvacho, O., Lu, Z., 1992. Measurements of fugitive PM10 emissions from selected agricultural practices in San Joaquin Valley. In: Chow, J.C., Ono, D.M. (Eds.), PM10 Standards and Nontraditional Particulate Source Controls. Trans. Air and Waste Management Association/EPA Int. Spec. Conf., TR-22, vol. 1, pp. 417–432.

McTainsh, G.H., Strong, C., 2007. The role of aeolian dust in ecosystems. Geomorphology 89, 39–54.

McTainsh, G.H., Chan, Y., McGowan, H., Leys, J., Tews, K., 2005. The 23rd October 2002 dust storm in eastern Australia: characteristics and meteorological conditions. Atmospheric Environment 39, 1227–1236.

Meloni, D., Di Sarra, A., Di Iorio, T., Fiocco, G., 2004. Direct radiative forcing of Saharan dust in the Mediterranean from measurements at Lampedusa Island and MISR

space-borne observations. Journal of Geophysical Research 109, D08206. doi:10.1029/2003JD003960.

Meng, Z., Lu, B., 2007. Dust events as a risk factor for daily hospitalization for respiratory and cardiovascular diseases in Minqin, China. Atmospheric Environment 41, 7048–7058.

Meskhidze, N., Chameides, W.L., Nenes, A., 2005. Dust and pollution: a recipe for enhanced ocean fertilization? Journal of Geophysical Research 110, D03301. doi:10.1029/2004JD005082.

Middleton, N.J., 1986. Dust storms in the Middle East. Journal of Arid Environments 10, 83–96.

Middleton, N.J., 1991. Dust storms in the Mongolian People's Republic. Journal of Arid Environments 20, 287–298.

Mikkelsen, J.H., Langohr, R., 1998. Impact of dust on soil evolution and fertility, case studies from northern Ghana and the Altai Mountains, SW Siberia. In: Busacca, A., Lilligren, S., Newell, K. (Eds.), Dust Aerosols, Loess Soils and Global Change: An Interdisciplinary Conference and Field Tour on Dust in Ancient Environments and Contemporary Environmental Management. Washington State University College of Agriculture and Home Economics, pp. 223–226. Miscellaneous Publication No. 190.

Moosmüller, H., Gillies, J.A., Rogers, C.F., DuBois, D.W., Chow, J.C., Watson, J.G., Langston, R., 1998. Particulate emission rates for unpaved shoulders along a paved road. Journal of the Air and Waste Management Association 48, 398–407.

MRI (midwest research institute), 2001. Revisions to AP-42 Section 13.2.2 "Unpaved Roads". Technical Memorandum prepared for the US EPA, Research Triangle Park, NC, Midwest Research Institute, Kansas City, MO.

Nicholson, K.W., Branson, J.R., Geiss, P., Cannel, R.J., 1989. The effects of vehicle activity on particle resuspension. Journal of Aerosol Science 20, 1425–1428.

Ozer, P., Ould Mohamed Laghdaf, M.B., Ould Mohamed Lemine, S., Gassani, J., 2007. Estimation of air quality degradation due to Saharan dust at Nouakchott, Mauritania, from horizontal visibility data. Water, Air, and Soil Pollution 178, 79–87.

Pelig-Ba, K.B., Parker, A., Price, M., 2001. Elemental contamination of rainwater by airborne dust in Tamale township area of the northern region of Ghana. Environmental Geochemistry and Health 23, 329–342.

Pinnick, R.G., Fernandez, G., Hinds, B.D., Bruce, C.W., Schaefer, R.W., Pendleton, J.D., 1985. Dust generated by vehicular traffic on unpaved roadways: sizes and infrared extinction characteristics. Aerosol Science and Technology 4, 99–121.

Prospero, J.M., 1999. Long-term measurements of the transport of African mineral dust to the southeastern United States: implications for regional air quality. Journal of Geophysical Research 104 (D13), 15917–15927.

Pye, K., Tsoar, H., 1990. Aeolian Sand and Sand Dunes. Unwin Hyman, London.

Reynolds, R.L., Belnap, J., Reheis, M., Lamothe, P., Luiszer, F., 2001. Aeolian dust in Colorado Plateau soils: nutrient inputs and recent change in source. Proceedings of the National Academy of Sciences of the United States of America 98, 7123–7127.

Reynolds, R.L., Yount, J.C., Reheis, M., Goldstein, H., Chavez Jr., P., Fulton, R., Whitney, J., Fuller, C., Forester, R.M., 2007. Dust emission from wet and dry playas in the Mojave Desert, USA. Earth Surface Processes and Landforms 32, 1811–1827.

Riksen, M. 2004. Off-site effects of wind erosion on agricultural land in northwestern Europe. In: Goossens, D., Riksen, M. (Eds.), Wind Erosion and Dust Dynamics: Observations, Simulations, Modelling. ESW Publications, Department of Environmental Sciences, Erosion and Soil and Water Conservation Group, Wageningen University, Wageningen, pp. 103–122.

Roda, F., Bellot, J., Avila, A., Escarre, A., Pinol, J., Terradas, J., 1993. Saharan dust and the atmospheric inputs of elements and alkalinity to Mediterranean ecosystems. Water, Air, and Soil Pollution 66, 277–288.

Schulz, D., 1992. Obergrenze für den Dioxingehalt von Ackerböden. Zeitschrift der Umweltchemie und Őkotoxikologie 4, 207–209.

Sharrat, B., Feng, G., Wendling, L., 2007. Loss of soil and PM10 from agricultural fields associated with high winds on the Columbia Plateau. Earth Surface Processes and Landforms 32, 621–630.

Shaw, G.E., 1980. Transport of Asian desert aerosol to the Hawaiian Islands. Journal of Applied Meteorology 19, 1254–1259.

Smith, J.L., Lee, K., 2003. Soil as a source of dust and implications for human health. Advances in Agronomy 80, 1–32.

Spivey, S., 2008. Off-road fans, critics face off. Las Vegas Review-Journal 10B Monday, March 17, 2008.

Squires, V.R., 2002. Dust storms and dust devils in south Australia: The driest province of the driest continent on Earth. In: Yang, Y., Squires, V.R., Lu, Q. (Eds.), Global Alarm: Dust and Sandstorms from the World's Drylands, United Nations Publication, pp. 155–166. E.02.II.F.50.

Sterk, G., Hermann, L., Bationo, A., 1996. Wind-blown nutrient transport and soil productivity change in southwest Niger. Land Degradation and Rehabilitation 7, 325–335.

Sun, Y., Zhuang, G., Yuan, H., Zhang, X., Guo, J., 2004. Characteristics and sources of 2002 super dust storm in Beijing. Chinese Science Bulletin 49, 698–705.

Takemi, T., Seino, N., 2005. Dust storms and cyclone tracks over the arid regions in east Asia in spring. Journal of Geophysical Research 110, D18S11. doi:10.1029/2004JD004698.

US EPA 1995. User's Guide for the Industrial Source Complex (ISC3) Dispersion Models. Vol. II: Description of Model Algorithms. US Environmental Protection Agency, Office of Air Quality Planning and Standards: Emissions, Monitoring, and Analysis Division, Research Triangle Park, North Carolina, USA.

US EPA 1996. Compilation of Air Pollutant Emission Factors. Vol. 1: Stationary Point and Area Sources. US EPA Office of Air and Radiation, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, USA.

US EPA, 1999. Compilation of air pollutant emission factors. Vol. I: stationary point and area sources. Report No. AP-42. US Environmental Protection Agency, Research Triangle Park, North Carolina, USA.

US EPA 2003. AP-42, Fifth Edition. Vol. 1: Miscellaneous Sources, Chapter 13. US Environmental Protection Agency, Research Triangle Park, North Carolina, USA.

Venkatram, A., 1999. A critique of empirical emission factor models: a case study of the AP-42 model for estimating PM10 emissions from paved roads. Atmospheric Environment 34, 1–11.

Venkatram, A., Fitz, D., Bumiller, K., Du, S., Boeck, M., Ganguly, C., 1999. Using a dispersion model to estimate emission rates of particulate matter from paved roads. Atmospheric Environment 33, 1093–1102.

Wilkening, K.E., Barrie, L.A., Engle, M., 2000. Trans-Pacific air pollution. Science 290, 65–67.

Xuan, J., Liu, G., Du, K., 2000. Dust emission inventory in Northern China. Atmospheric Environment 34, 4565–4570.

Zhang, J., Liu, S.M., Lu, X., Huang, W., 1993. Characterizing Asian wind-dust transport to the Northwest Pacific Ocean: direct measurements of the dust flux for two years. Tellus B 45, 33–39.

Zhou, M., Okada, K., Qian, F., Wu, P., Su, L., Casareto, B.E., Shimohara, T., 1996. Characteristics of dust-storm particles and their long-range transport from China to Japan. Case studies in April 1993. Atmospheric Research 40, 19–31.